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Ok et al.

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(54) **VERTICAL NANO-WIRE COMPLIMENTARY METAL-OXIDE-SEMICONDUCTOR TRANSISTOR WITH CYLINDRICAL III-V COMPOUND AND GERMANIUM CHANNEL**

(58) **Field of Classification Search**
None
See application file for complete search history.

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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Primary Examiner — Benjamin P Sandvik

(22) Filed: **Jan. 16, 2020**

(74) *Attorney, Agent, or Firm* — Fleit Intellectual Property Law; Thomas S. Grzesik

(65) **Prior Publication Data**

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(57) **ABSTRACT**

Related U.S. Application Data

(62) Division of application No. 16/009,406, filed on Jun. 15, 2018, now Pat. No. 10,608,114.

A semiconductor structure and a method for fabricating the same. The semiconductor structure includes a substrate and a first source/drain layer in contact with at least the substrate. A vertical channel including indium gallium arsenide or germanium contacts at least the first/source drain layer. A gate structure contacts at least the vertical channel. A second source/drain layer contacts at least inner sidewalls of the vertical channel. The method includes epitaxially growing one or more fin structures comprising gallium arsenide in contact with a portion of a substrate. A separate channel layer comprising indium gallium arsenide or germanium is formed in contact with a respective one of the one or more fin structures.

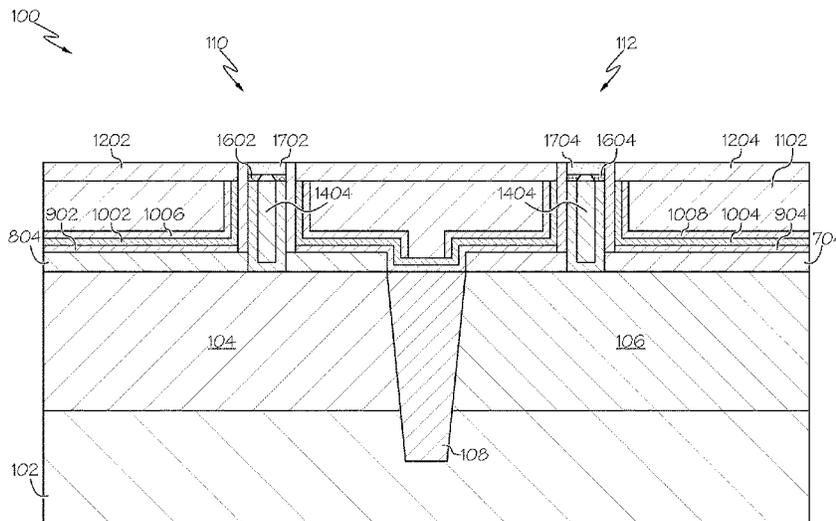
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H01L 29/205 (2006.01)
H01L 29/66 (2006.01)
H01L 29/16 (2006.01)

(52) **U.S. Cl.**

CPC **H01L 29/78642** (2013.01); **H01L 29/16** (2013.01); **H01L 29/205** (2013.01); **H01L 29/66462** (2013.01); **H01L 29/66666** (2013.01)

19 Claims, 20 Drawing Sheets



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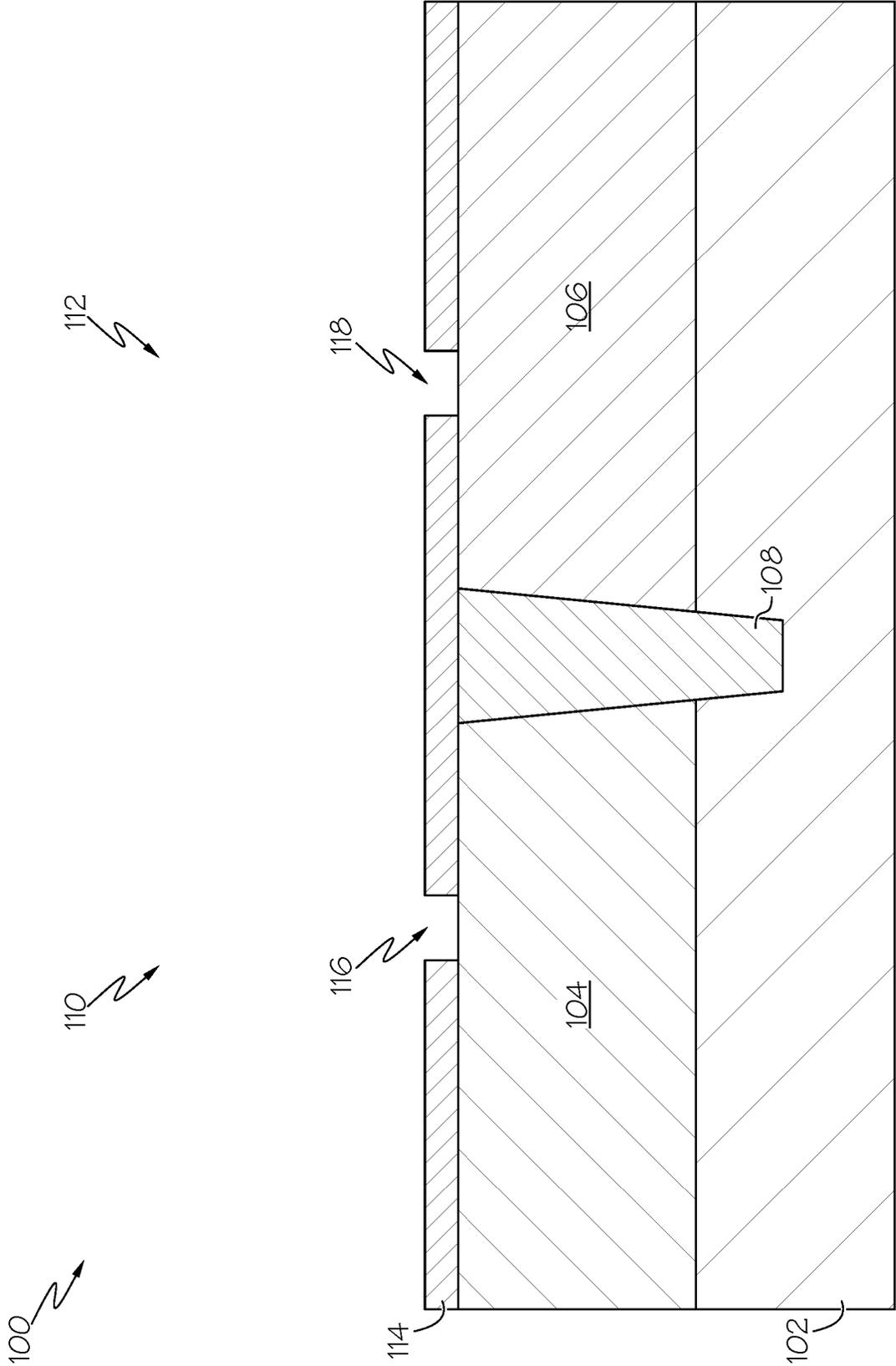


FIG. 1

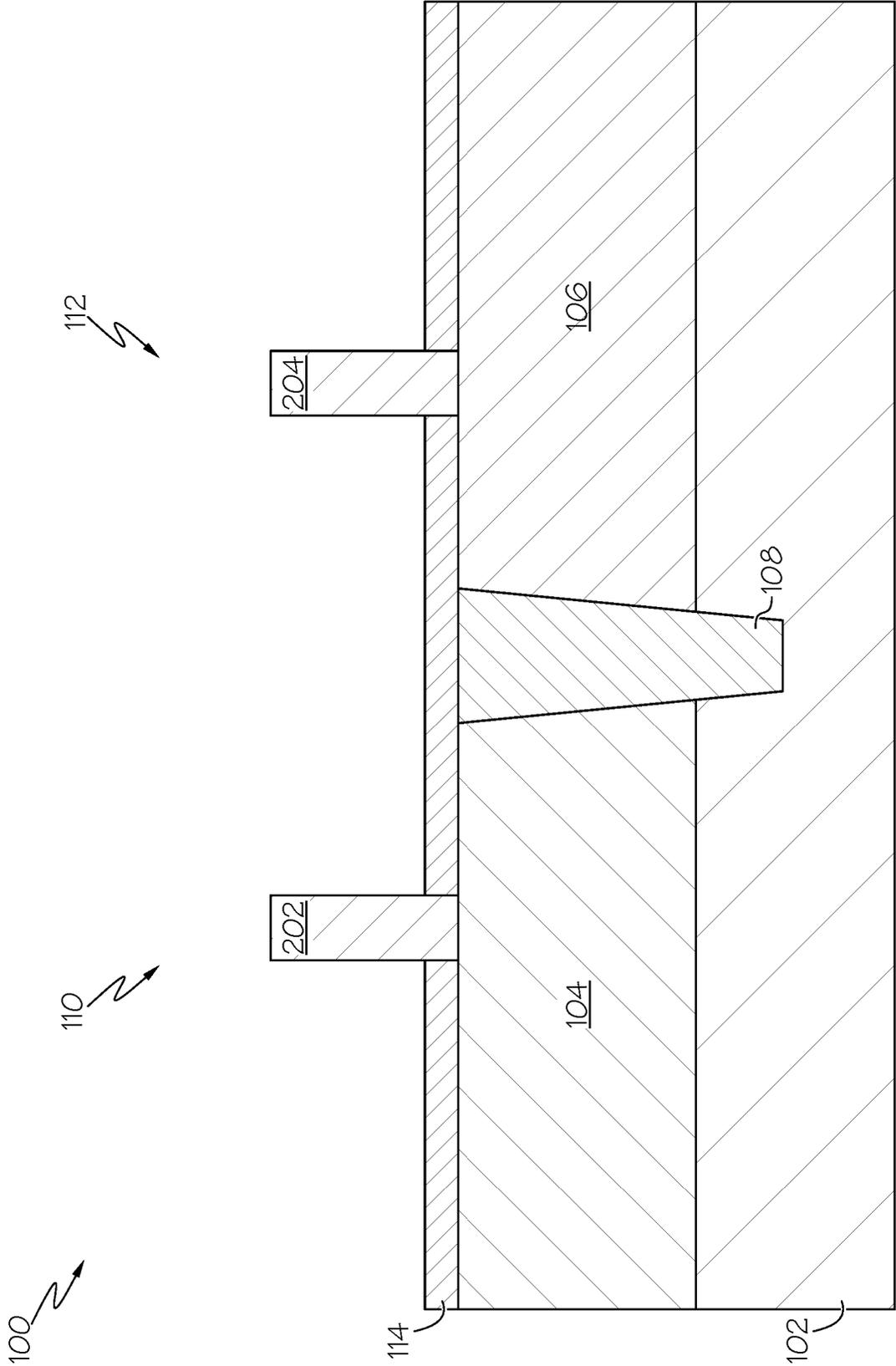


FIG. 2

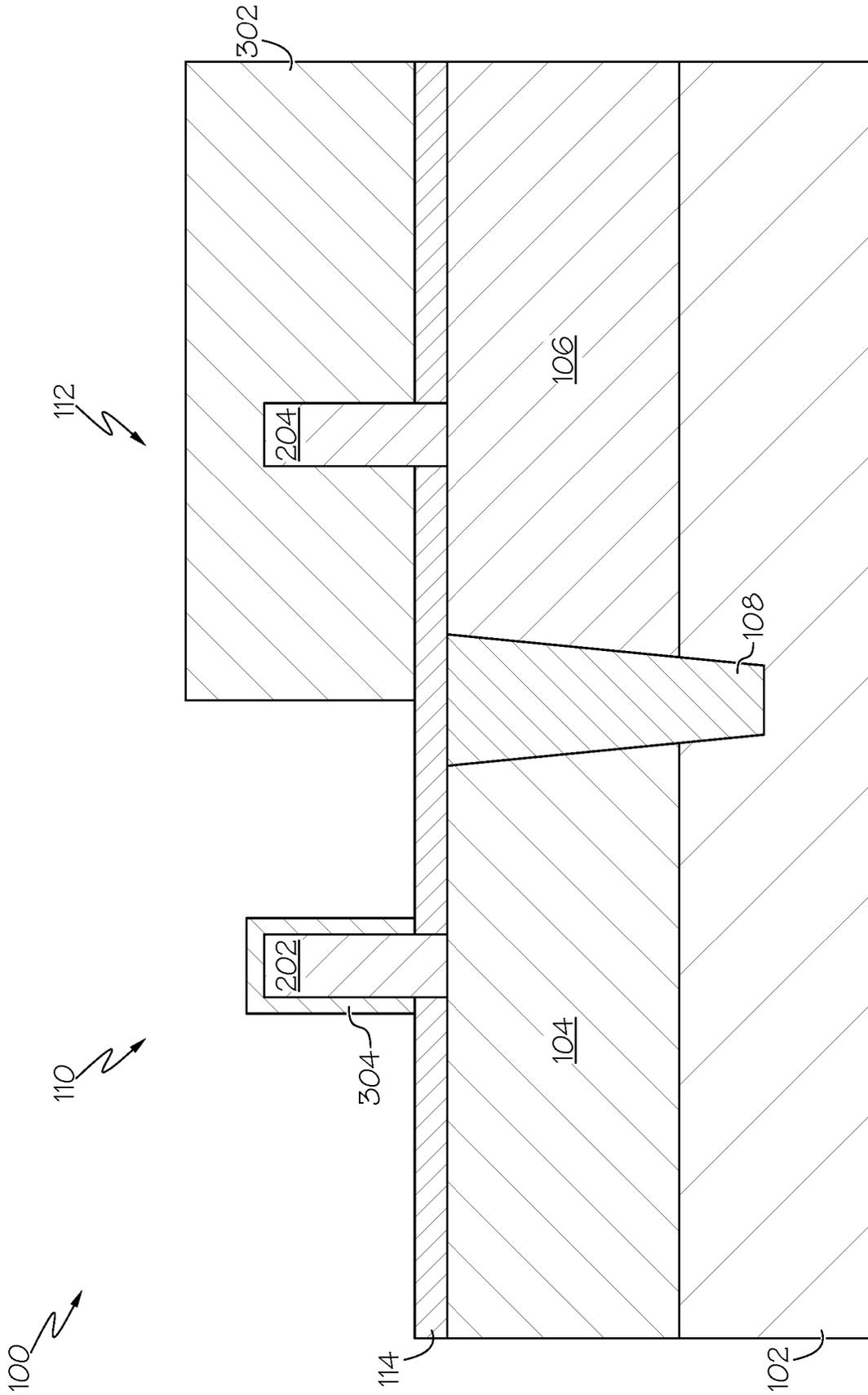


FIG. 3

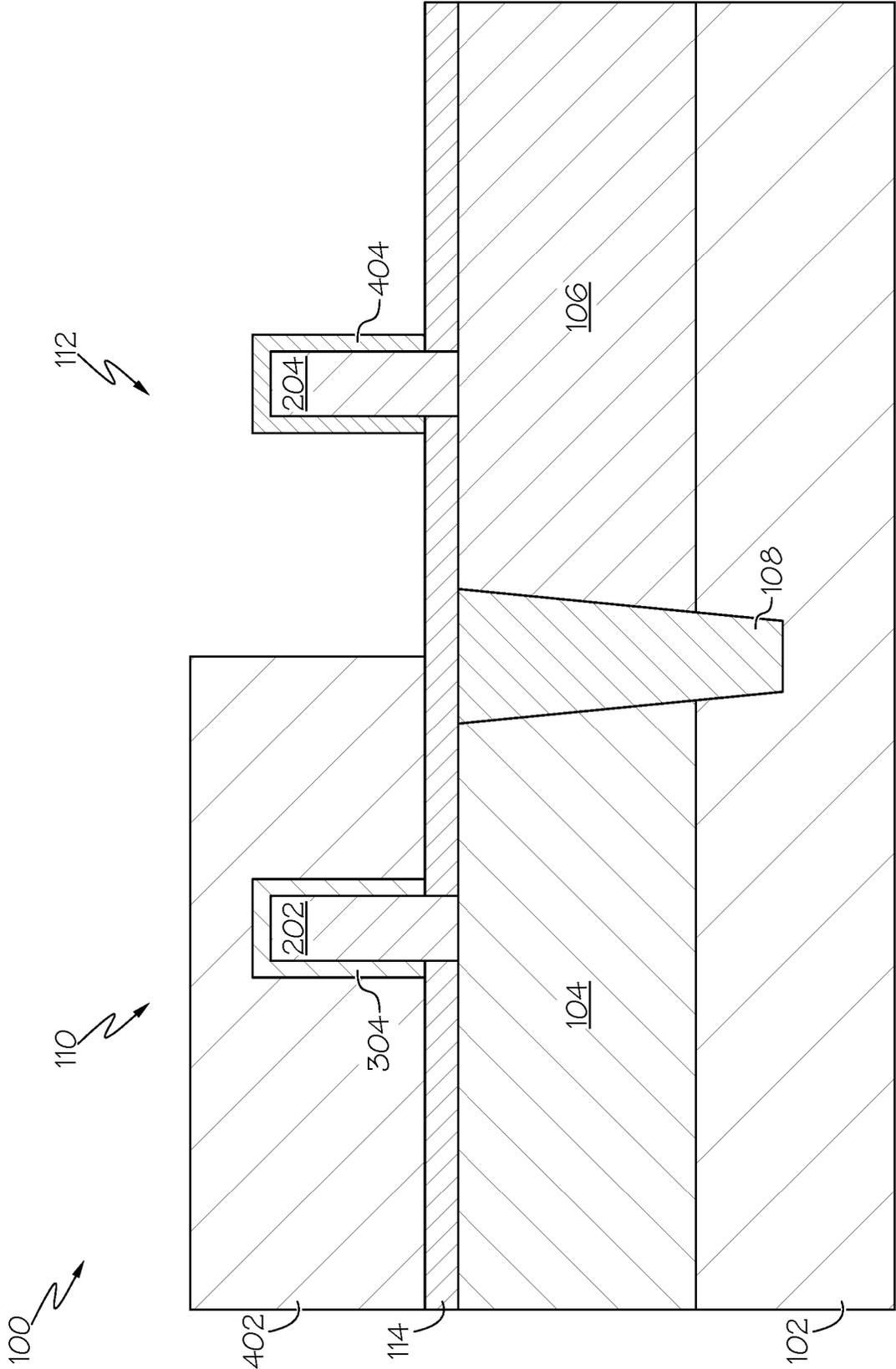


FIG. 4

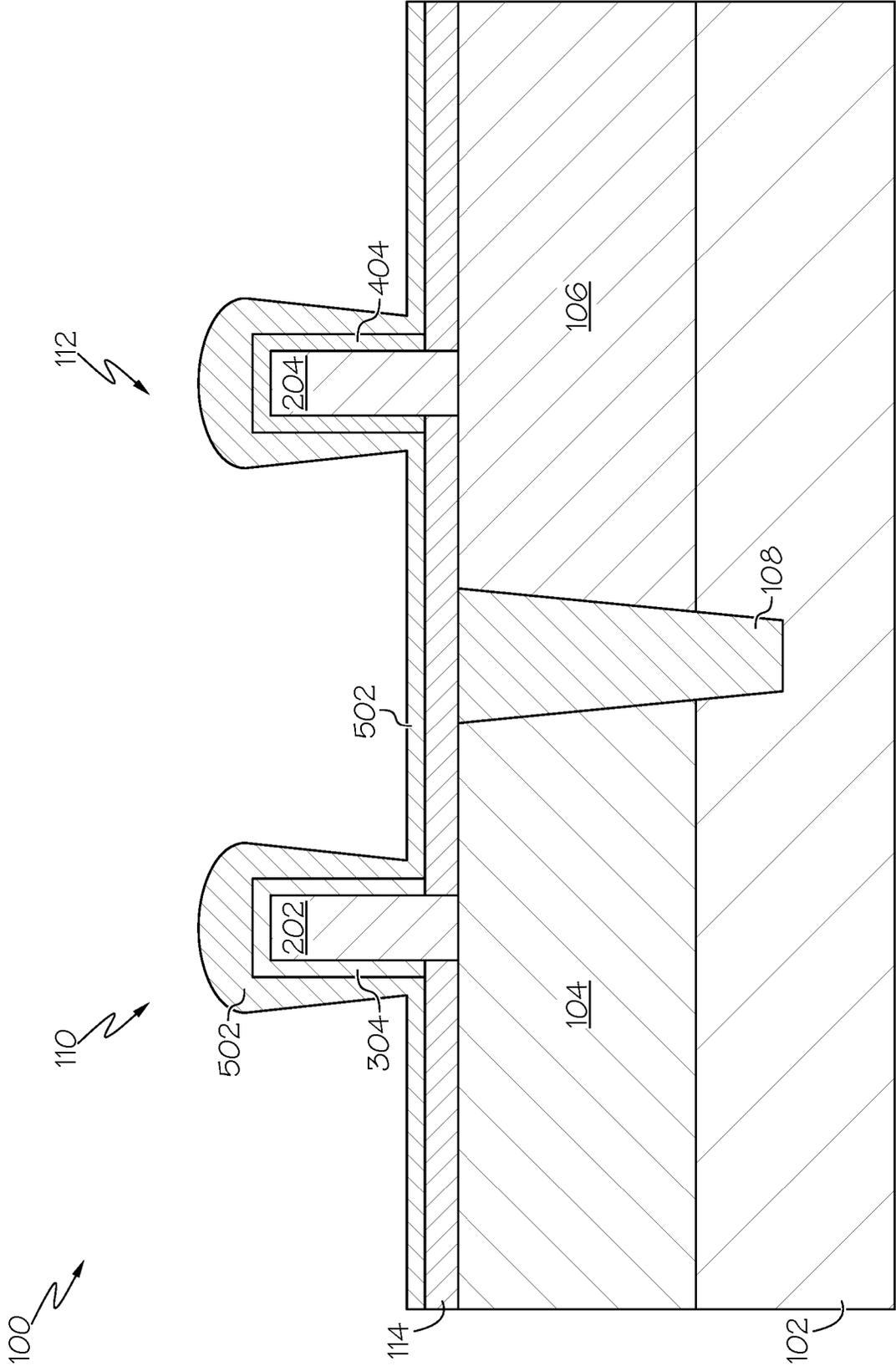


FIG. 5

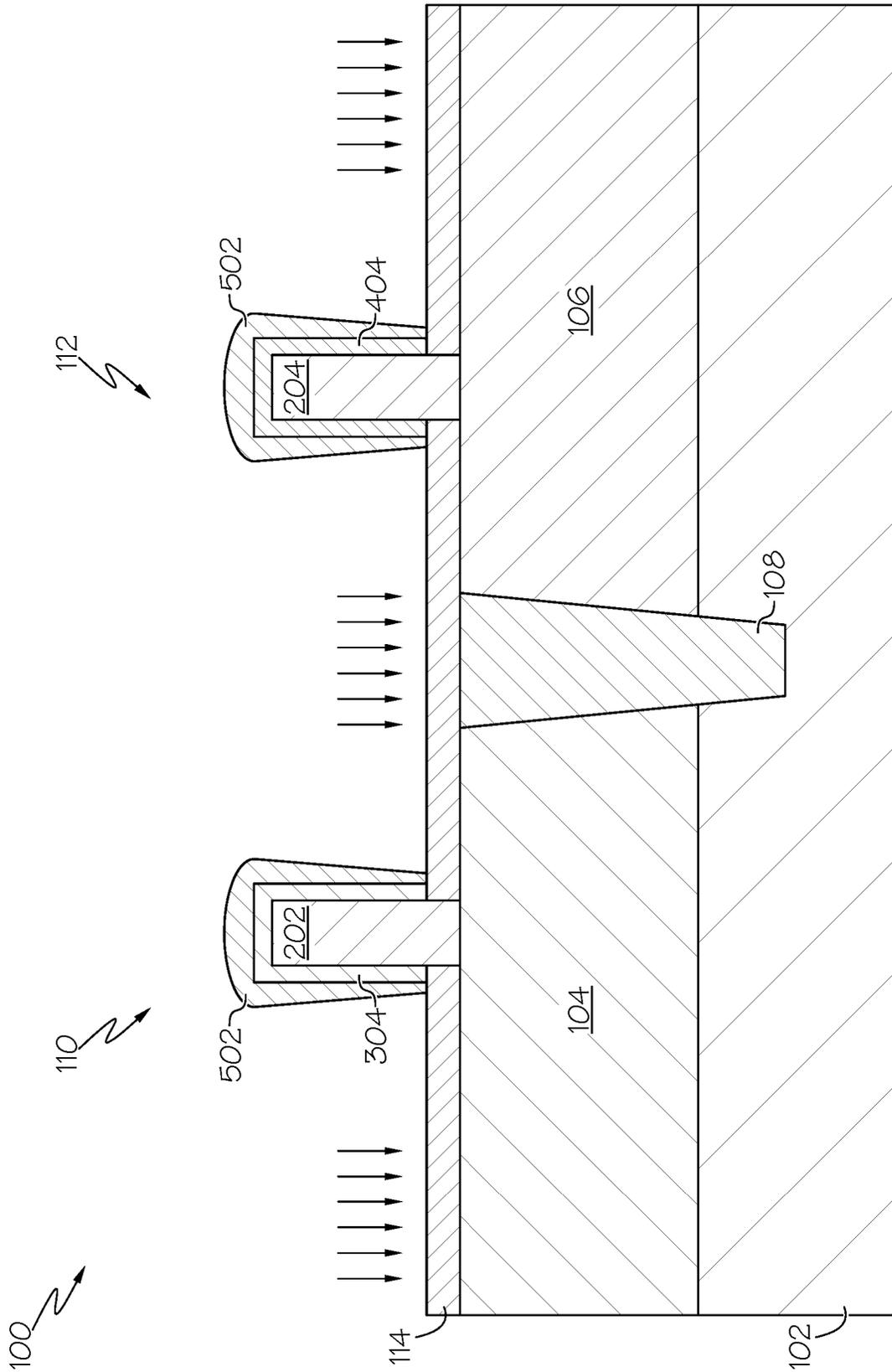


FIG. 6

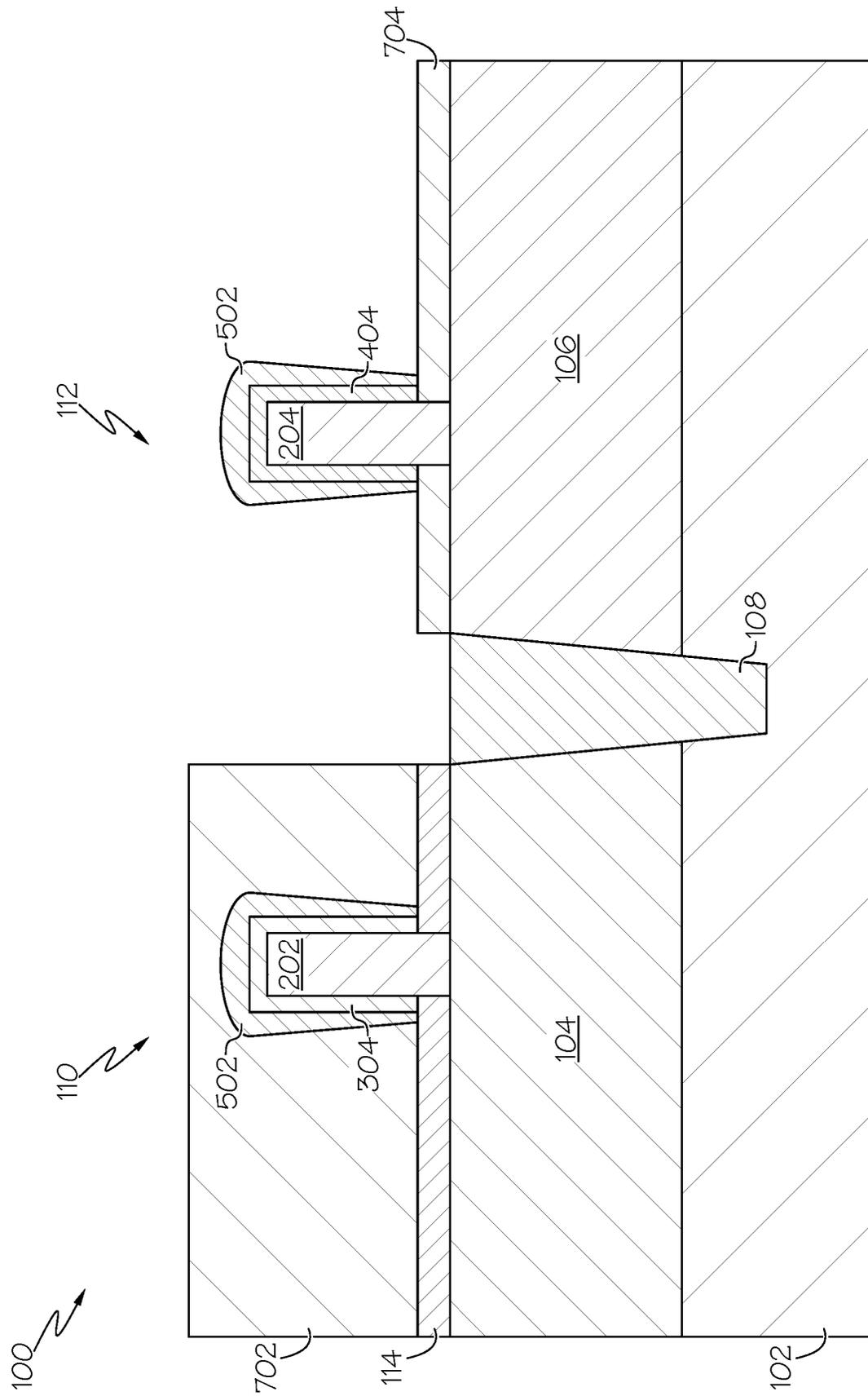


FIG. 7

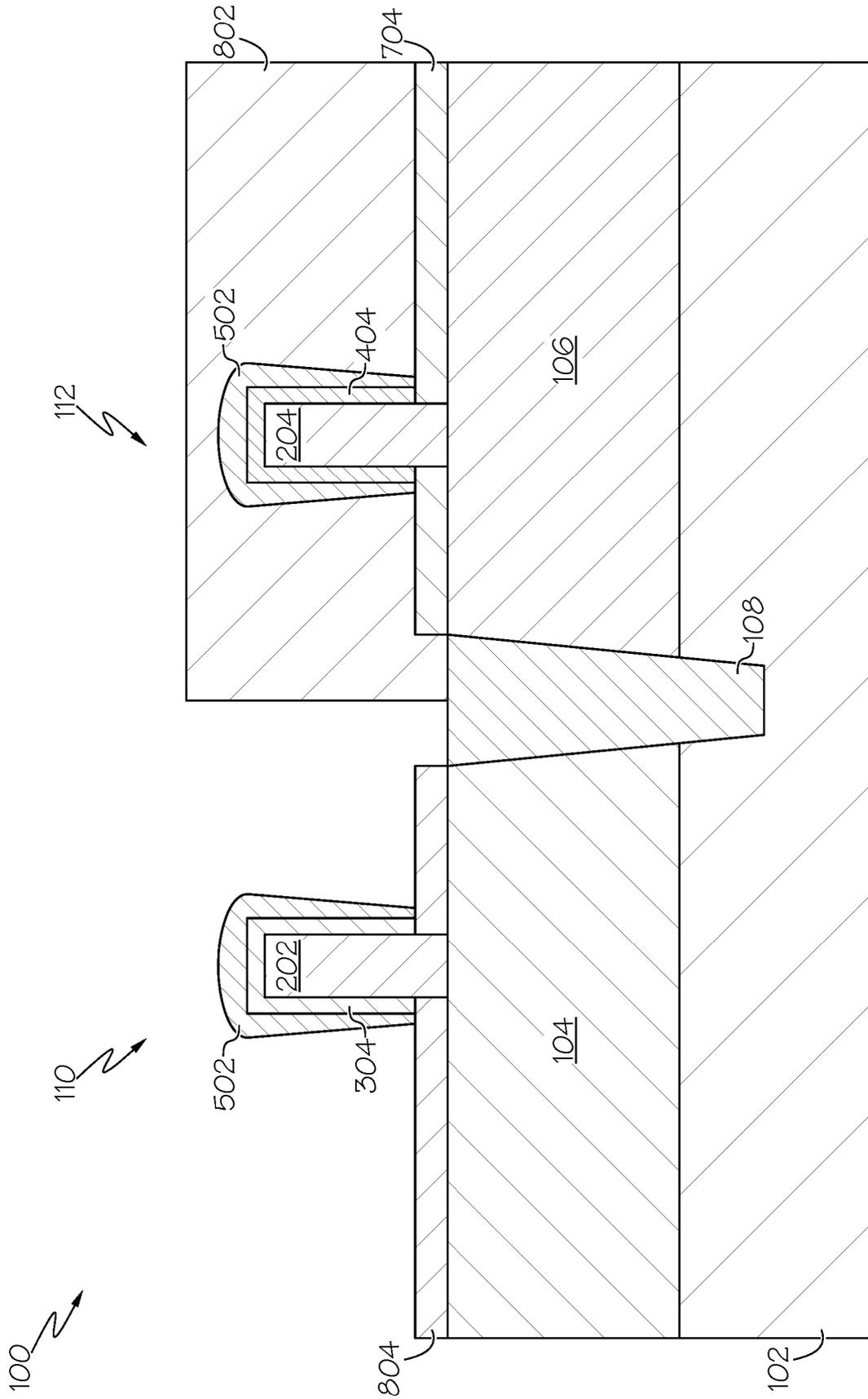


FIG. 8

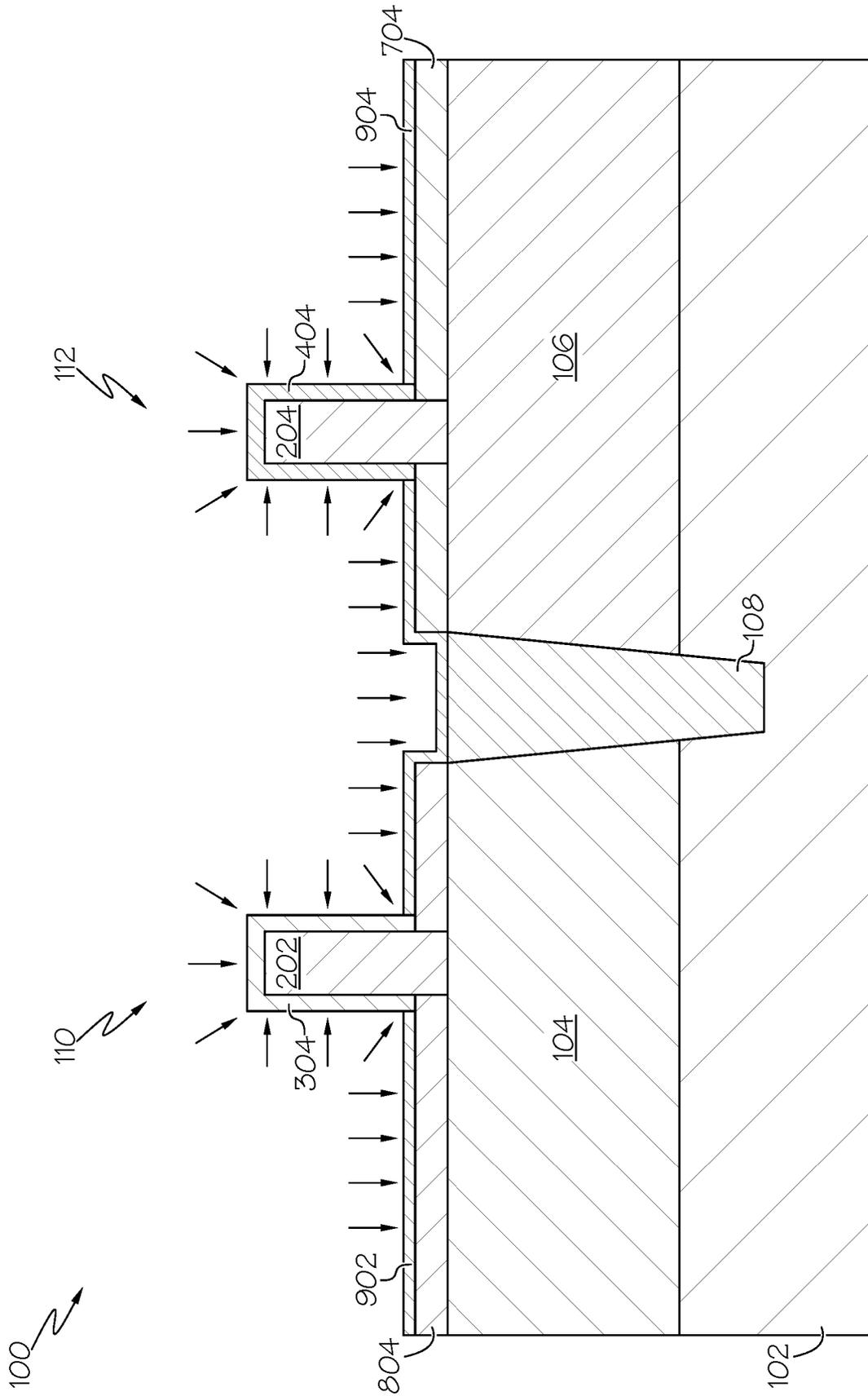


FIG. 9

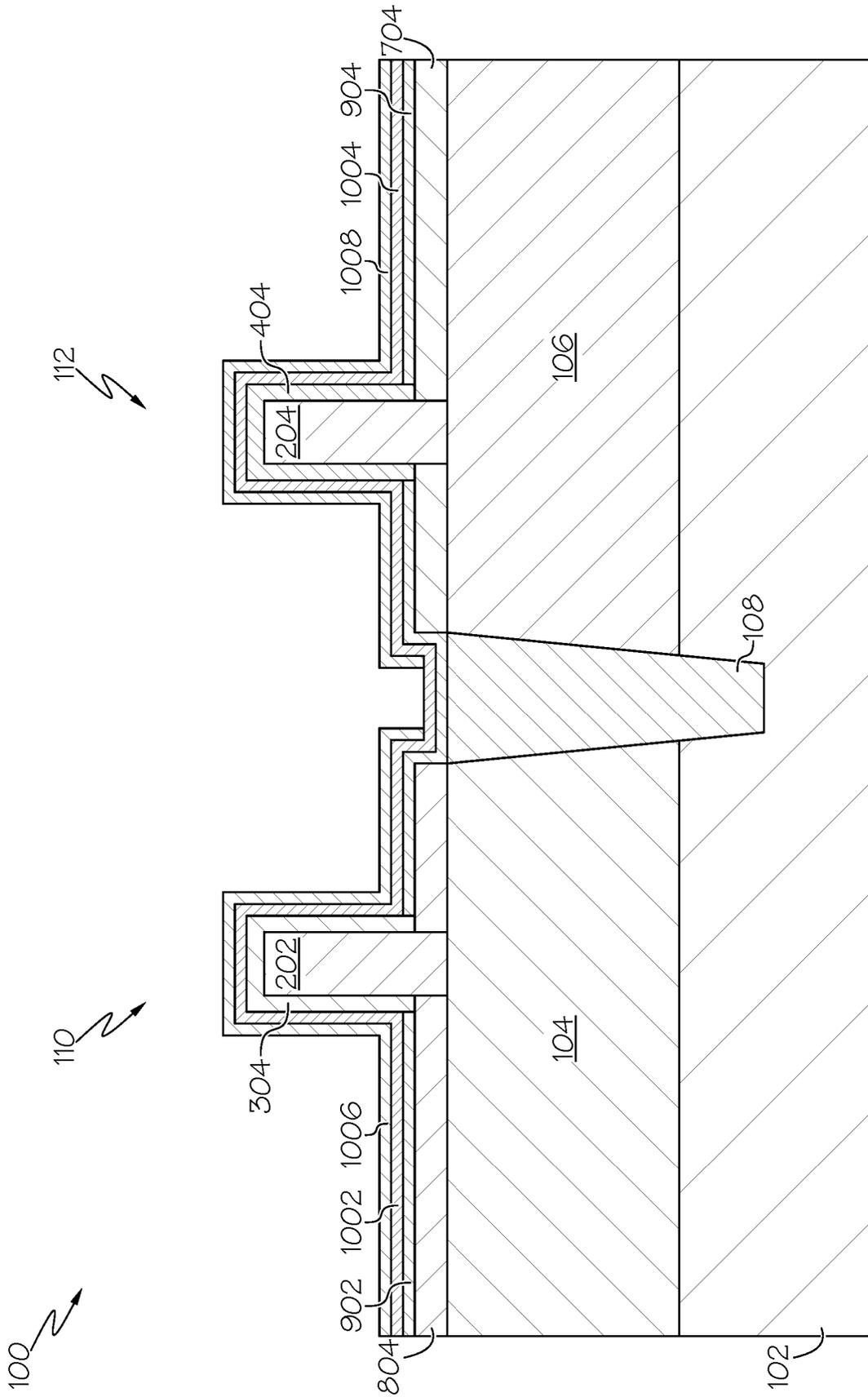


FIG. 10

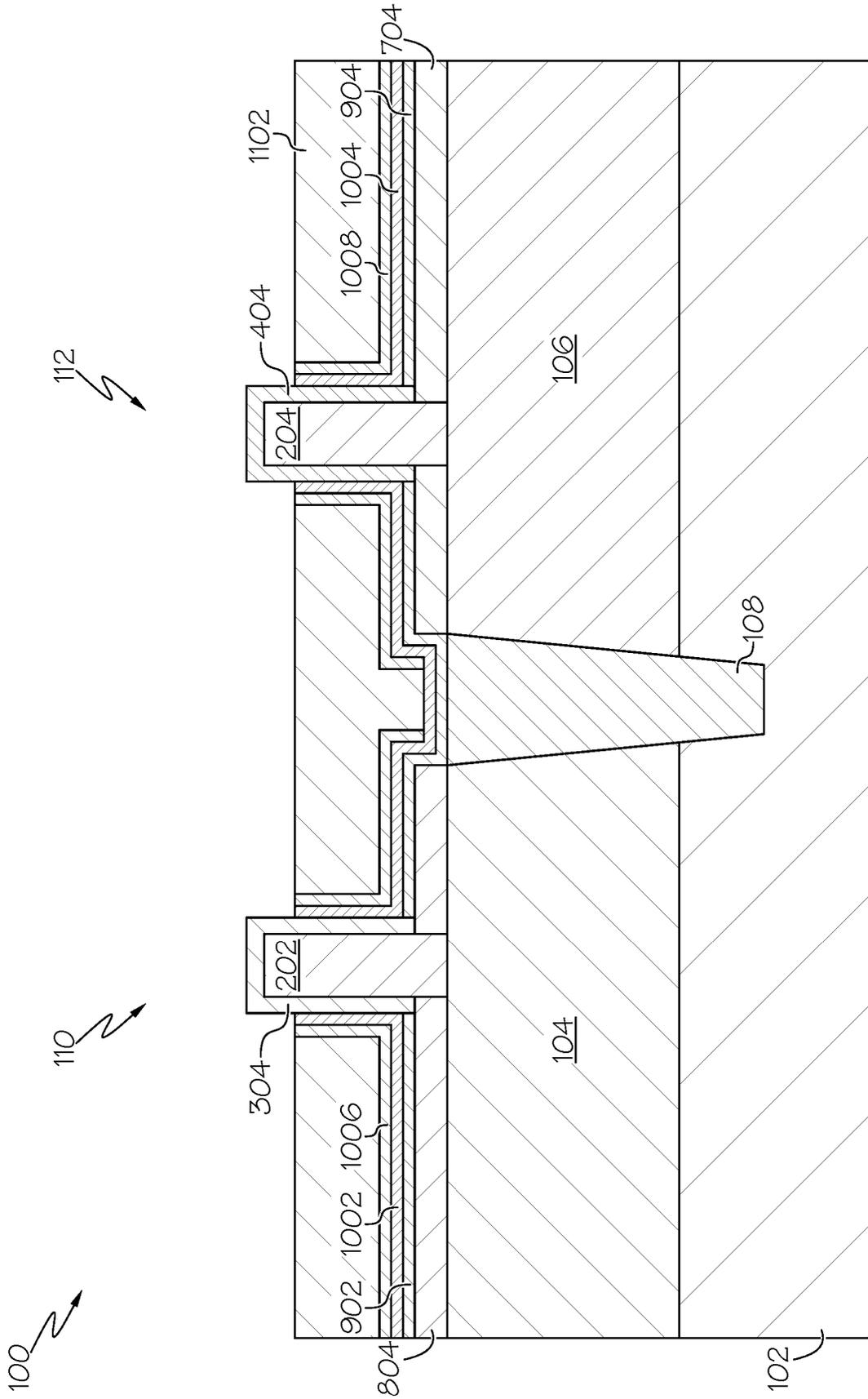


FIG. 11

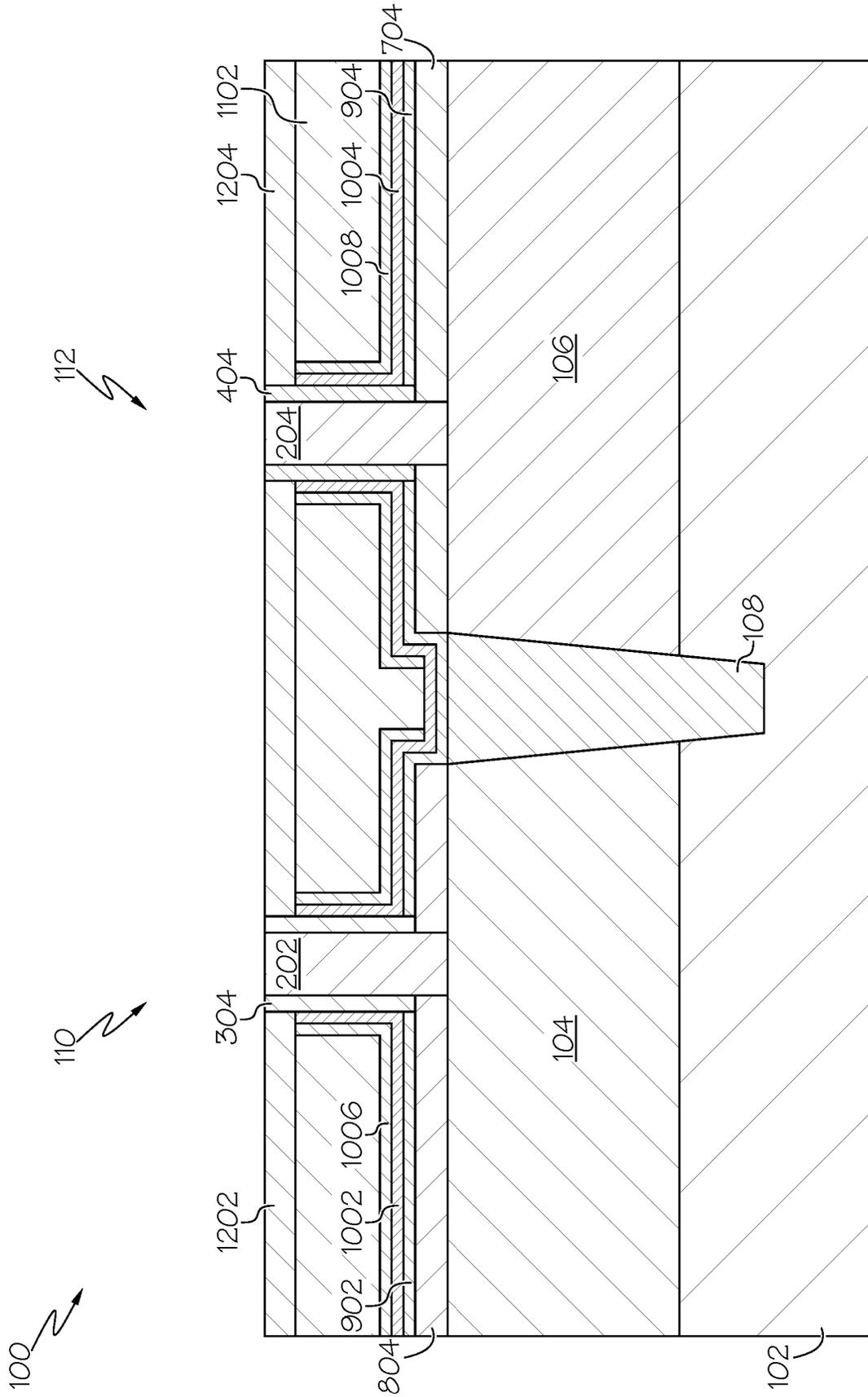


FIG. 12

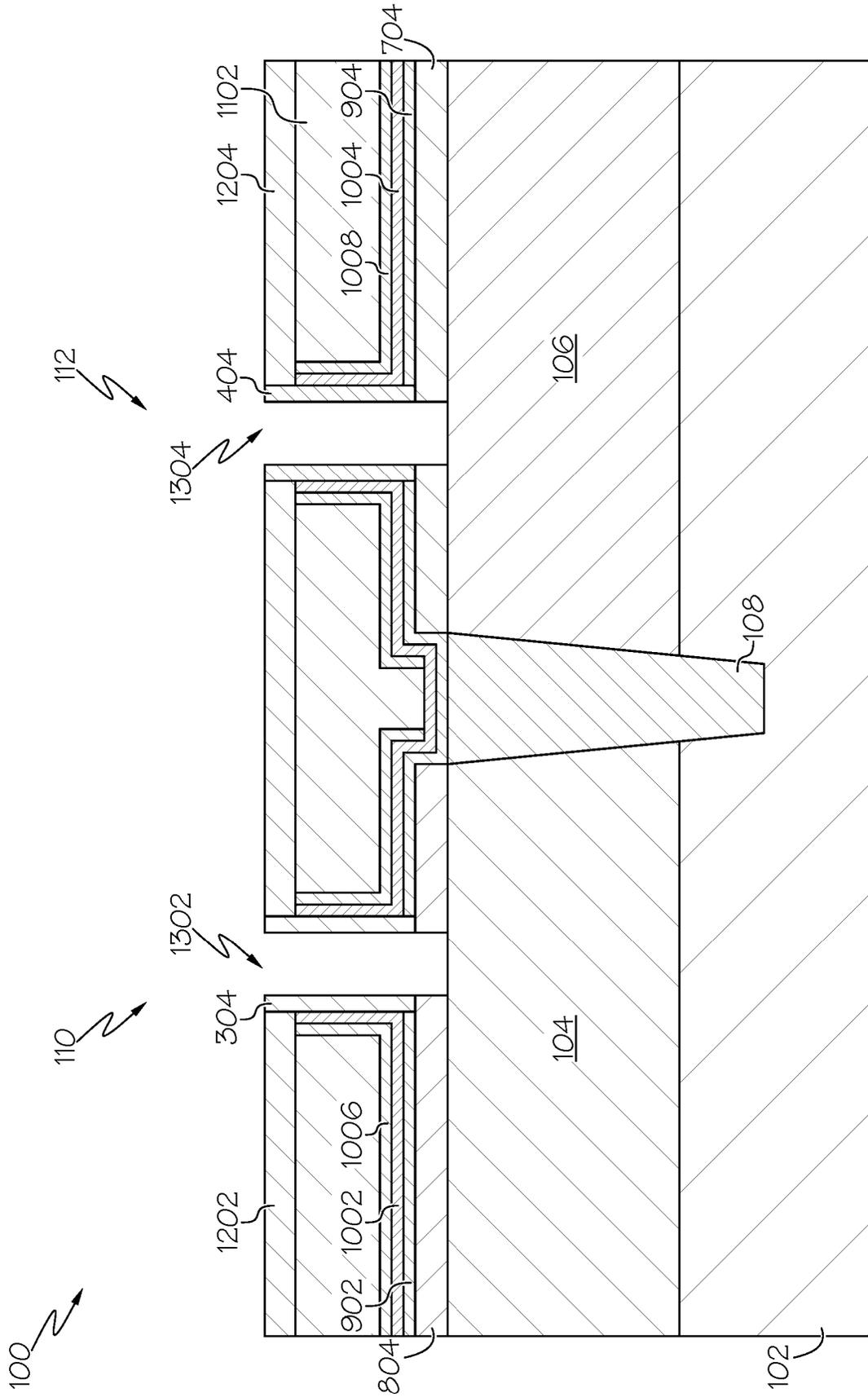


FIG. 13

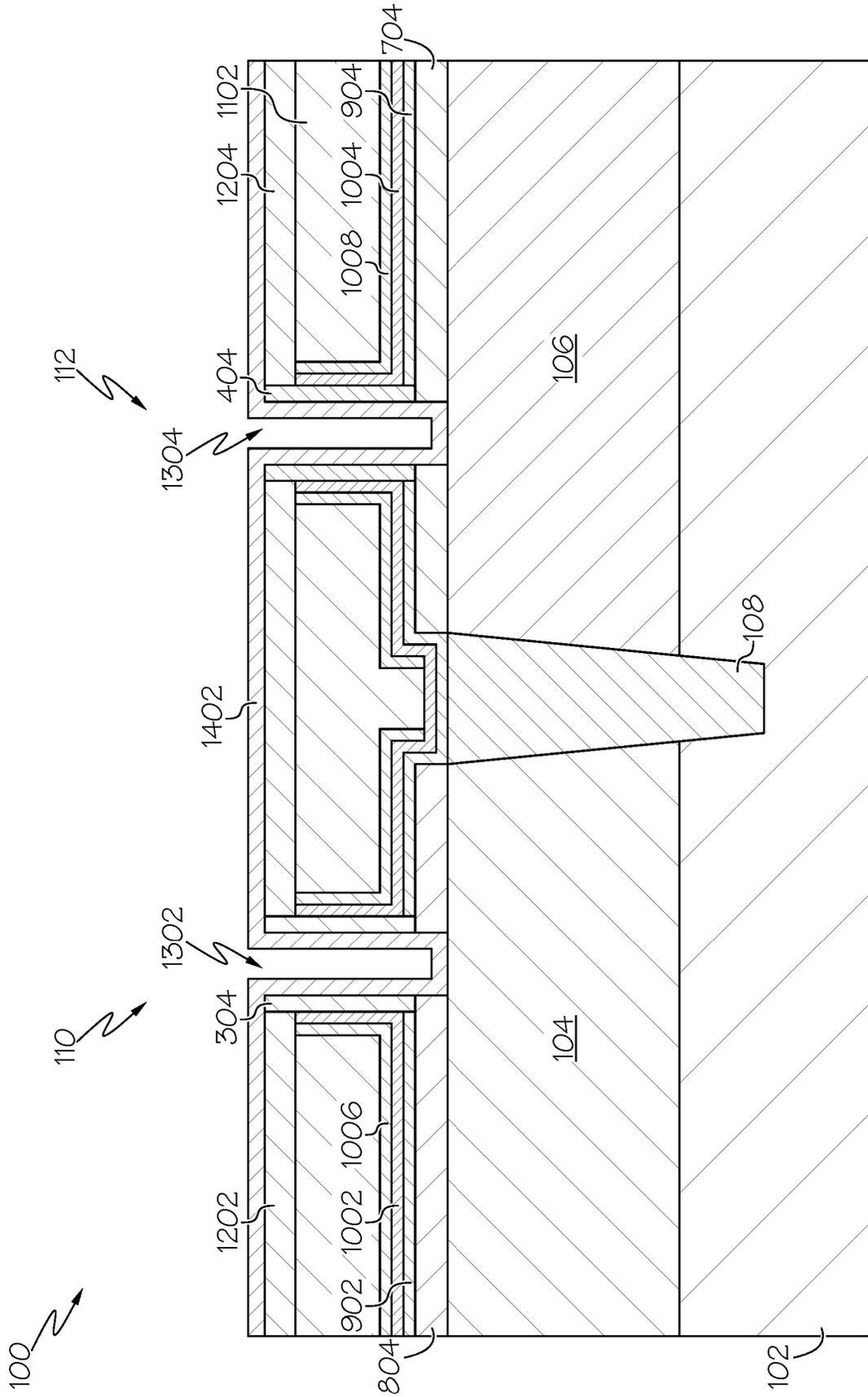


FIG. 14

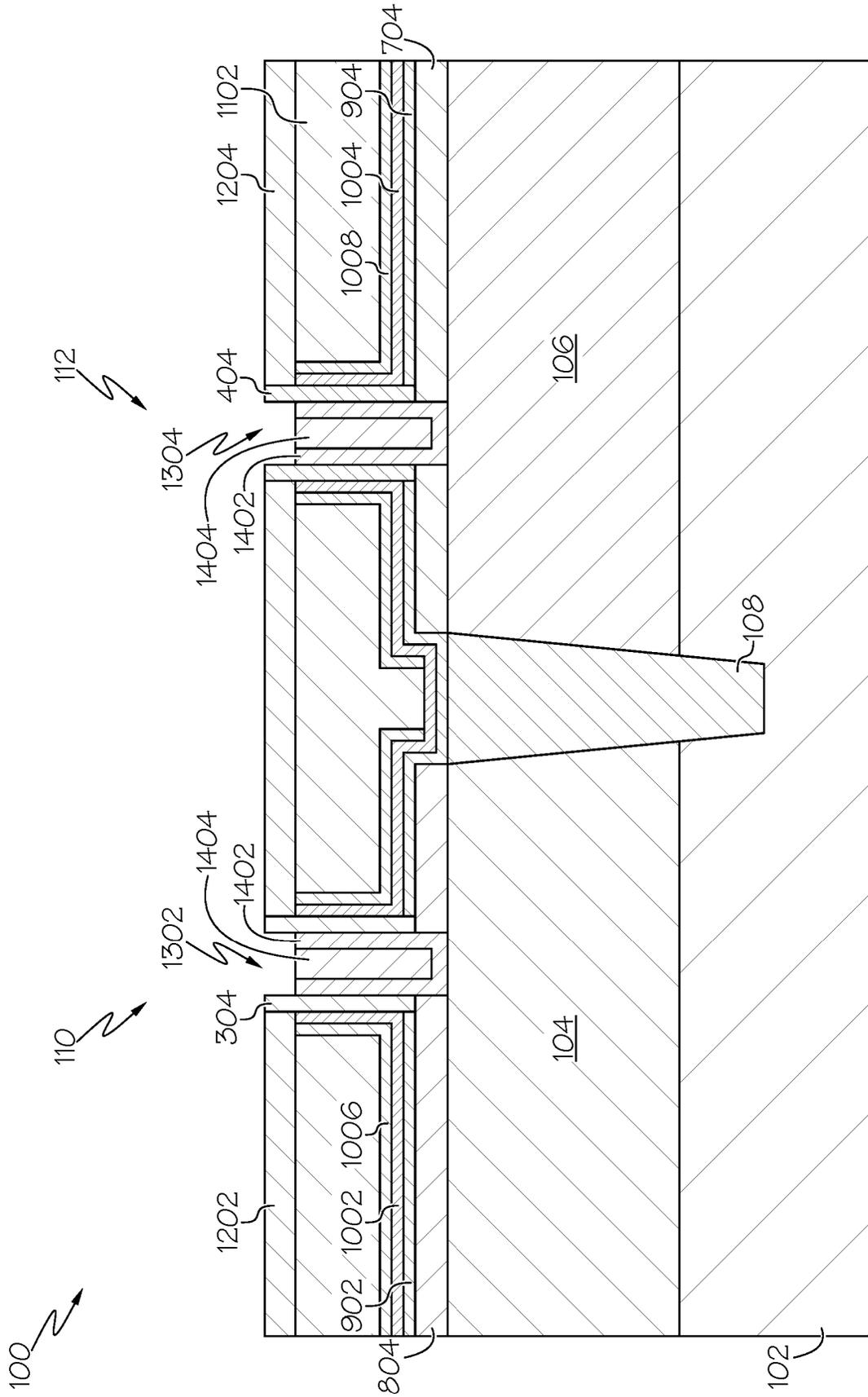


FIG. 15

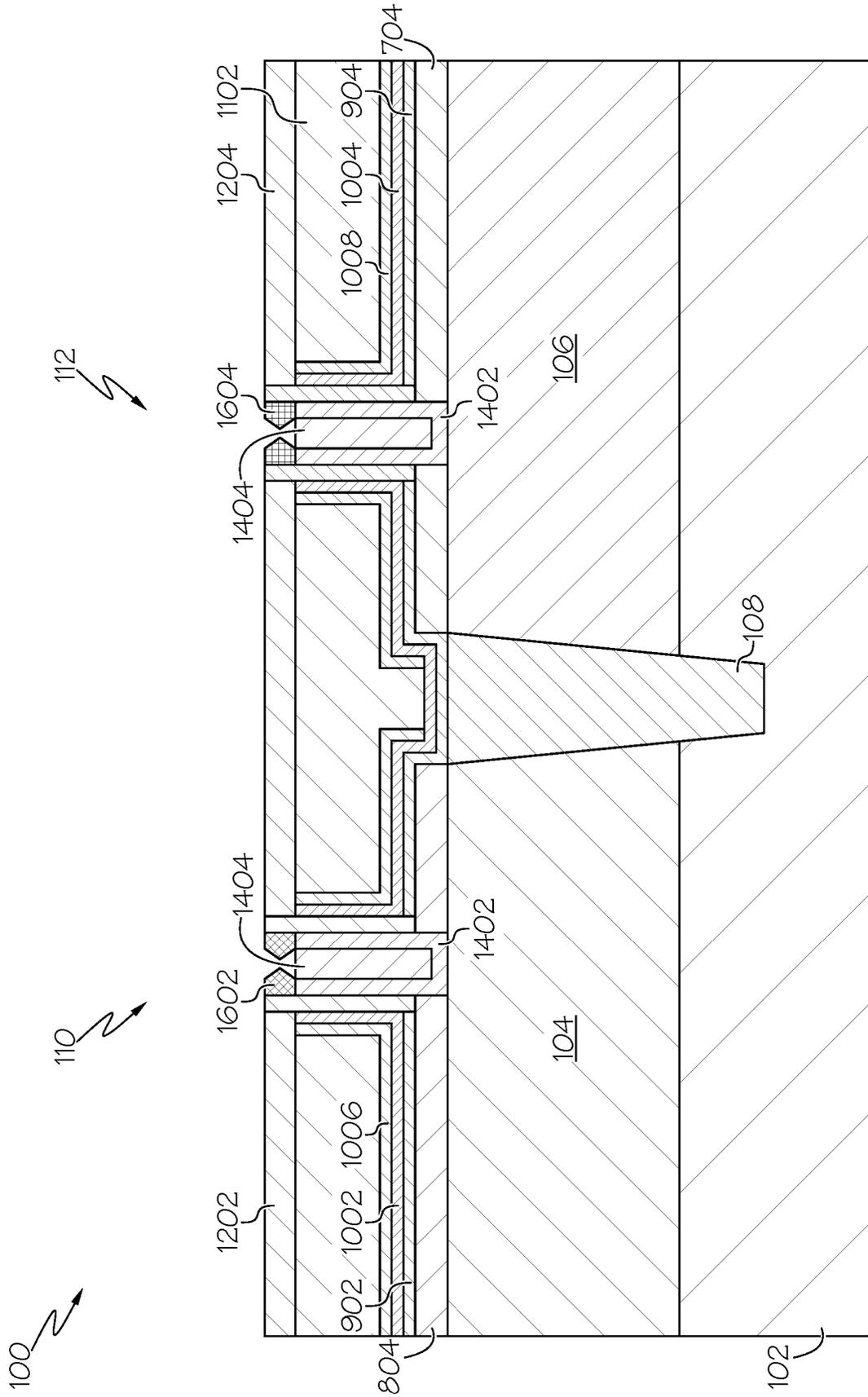


FIG. 16

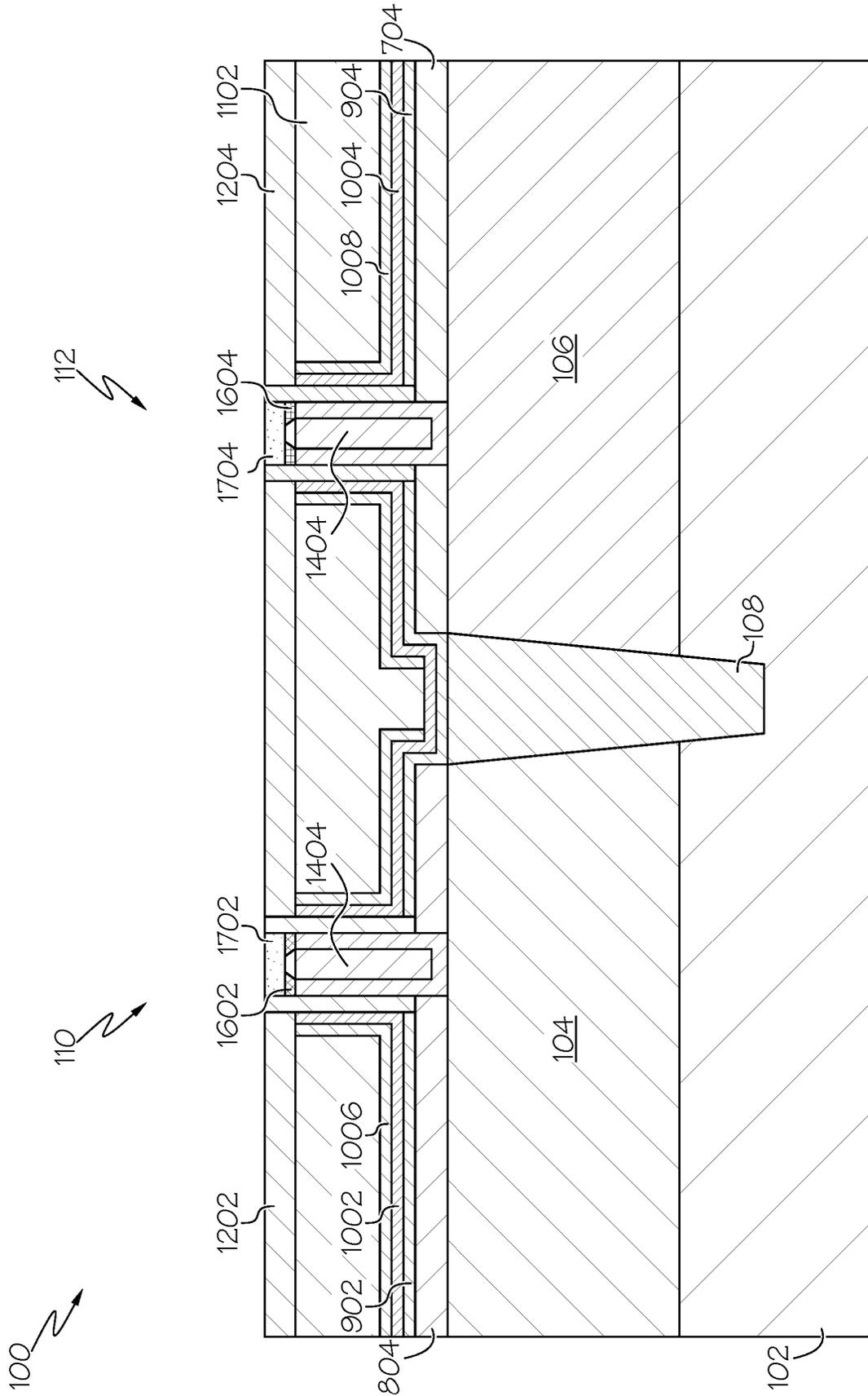


FIG. 17

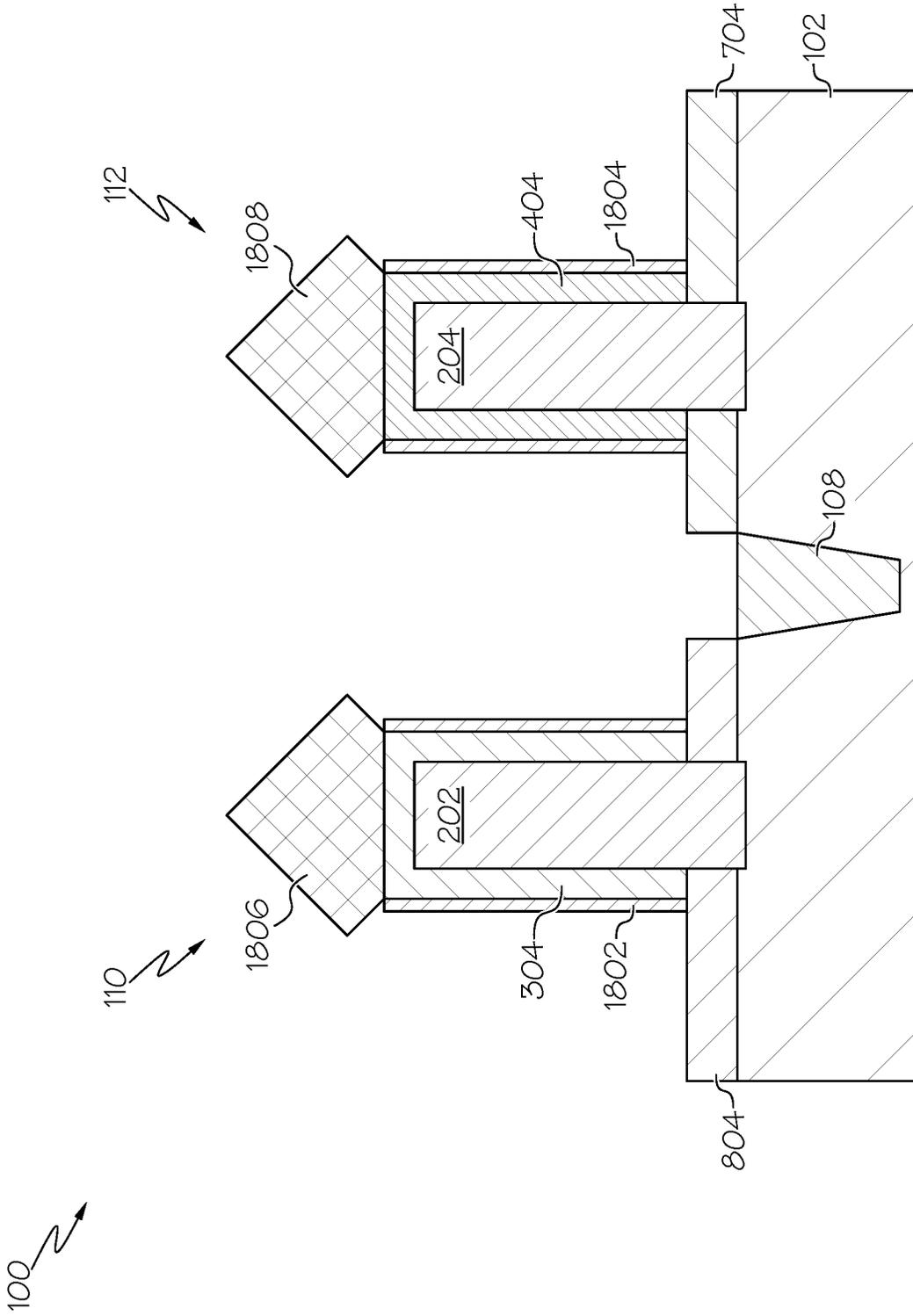


FIG. 18

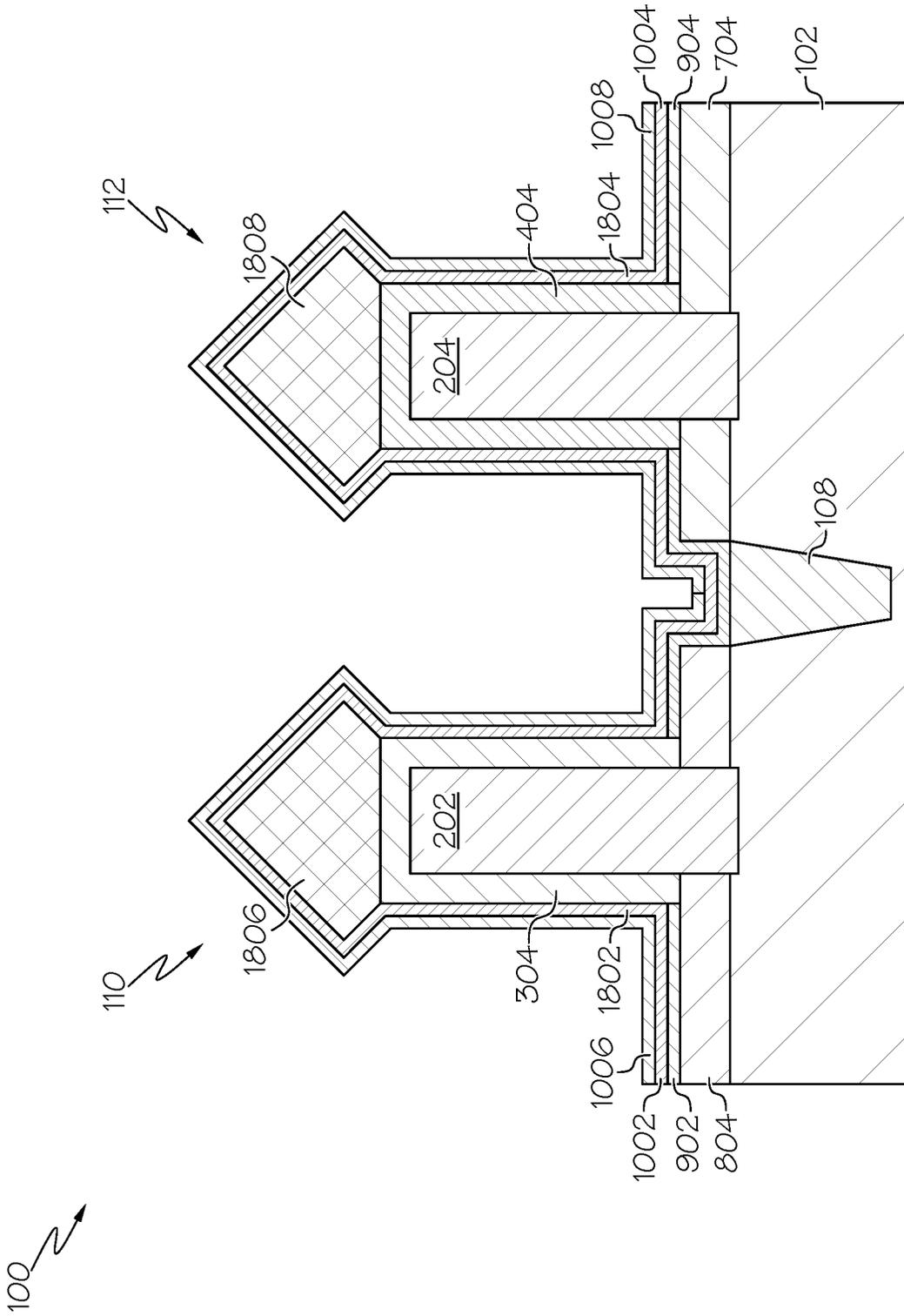


FIG. 19

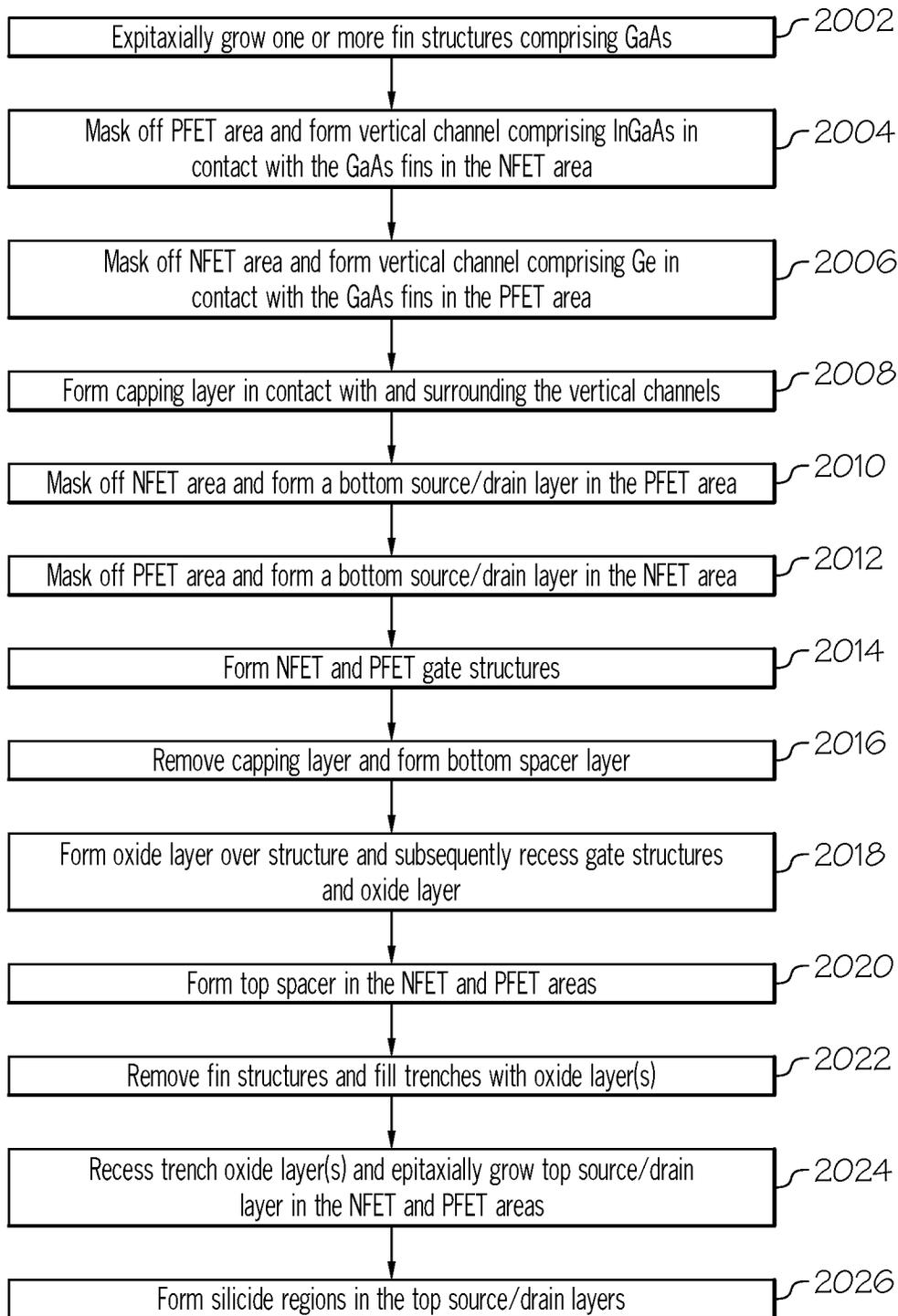


FIG. 20

**VERTICAL NANO-WIRE COMPLIMENTARY
METAL-OXIDE-SEMICONDUCTOR
TRANSISTOR WITH CYLINDRICAL III-V
COMPOUND AND GERMANIUM CHANNEL**

BACKGROUND OF THE INVENTION

The present disclosure generally relates to the field of semiconductors, and more particularly relates to vertical field effect transistors with III-V and germanium channels.

As silicon CMOS technology reaches its fundamental scaling limits, alternative materials such as high mobility III-V compounds (e.g., indium gallium arsenide) and silicon germanium have proven to be strong contenders for extending high performance logic. However, integrating free standing indium gallium arsenide and silicon germanium nanostructures on silicon has been difficult for current fabrication processes due to defect and chemistry incompatibilities.

SUMMARY OF THE INVENTION

In one embodiment, a method for forming a semiconductor structure is disclosed. The method comprises at least the following operations. One or more fin structures comprising gallium arsenide are epitaxially grown in contact with a portion of a substrate. A separate channel layer comprising indium gallium arsenide or germanium is formed in contact with a respective one of the one or more fin structures.

In another embodiment, a semiconductor structure is disclosed. The semiconductor structure comprises at least a substrate; and a first source/drain layer in contact with at least the substrate; a vertical channel including indium gallium arsenide or germanium in contact with at least the first/source drain layer; a gate structure in contact with at least the vertical channel; and a second source/drain layer in contact with at least inner sidewalls of the vertical channel.

In a further embodiment, an additional semiconductor structure is disclosed. The semiconductor structure comprises at least a substrate; and a first source/drain layer in contact with at least the substrate; a vertical channel including germanium in contact with at least the first/source drain layer and surrounding one or more oxide layers; a gate structure in contact with at least the vertical channel; and a second source/drain layer in contact with at least inner sidewalls of the vertical channel.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying figures where like reference numerals refer to identical or functionally similar elements throughout the separate views, and which together with the detailed description below are incorporated in and form part of the specification, serve to further illustrate various embodiments and to explain various principles and advantages all in accordance with the present invention, in which:

FIG. 1 is a cross-sectional view of a semiconductor structure after areas of an insulating layer have been patterned for formation of fin structures according one embodiment of the present disclosure;

FIG. 2 is a cross-sectional view of the semiconductor structure after fin structures have been formed according one embodiment of the present disclosure;

FIG. 3 is a cross-sectional view of the semiconductor structure after a III-V vertical channel layer has been formed on a fin structure in an NFET area of the semiconductor structure according one embodiment of the present disclosure;

FIG. 4 is a cross-sectional view of the semiconductor structure after a germanium vertical channel layer has been formed on a fin structure in a PFET area of the semiconductor structure according one embodiment of the present disclosure;

FIG. 5 is a cross-sectional view of the semiconductor structure after a capping layer has been formed over the structure according one embodiment of the present disclosure;

FIG. 6 is a cross-sectional view of the semiconductor structure after portions of the capping layer have been removed from the insulating layer according one embodiment of the present disclosure;

FIG. 7 is a cross-sectional view of the semiconductor structure after a bottom source/drain layer has been formed in the PFET area of the semiconductor structure according one embodiment of the present disclosure;

FIG. 8 is a cross-sectional view of the semiconductor structure after a bottom source/drain layer has been formed in the NFET area of the semiconductor structure according one embodiment of the present disclosure;

FIG. 9 is a cross-sectional view of the semiconductor structure after the capping layers have been removed from the vertical structures and a bottom spacer layer has been formed in the NFET and PFET areas of the semiconductor structure according one embodiment of the present disclosure;

FIG. 10 is a cross-sectional view of the semiconductor structure after gate structures have been formed according one embodiment of the present disclosure;

FIG. 11 is a cross-sectional view of the semiconductor structure after portions of an oxide layer and portions of the gate structures have been recessed according one embodiment of the present disclosure;

FIG. 12 is a cross-sectional view of the semiconductor structure after a top spacer layer has been formed in the NFET and PFET areas of the semiconductor structure according one embodiment of the present disclosure;

FIG. 13 is a cross-sectional view of the semiconductor structure after the fin structures have been removed according one embodiment of the present disclosure;

FIG. 14 is a cross-sectional view of the semiconductor structure after a capping layer and an oxide layer have been formed according one embodiment of the present disclosure;

FIG. 15 is a cross-sectional view of the semiconductor structure after the capping layer and oxide layer have been recessed according one embodiment of the present disclosure;

FIG. 16 is a cross-sectional view of the semiconductor structure after top source drain layers have been formed in the NFET and PFET areas of the semiconductor structure according one embodiment of the present disclosure;

FIG. 17 is a cross-sectional view of the semiconductor structure after silicide regions have been formed in the top source drain layers according one embodiment of the present disclosure;

FIG. 18 is a cross-sectional view of the semiconductor structure illustrating one additional embodiment for forming the bottom source/drain layers where a top epitaxial layer is formed as a result of forming the bottom source/drain layers according one embodiment of the present disclosure;

FIG. 19 is a cross-sectional view of the semiconductor structure after gate structures have been formed over the top epitaxial layers of FIG. 18 according one embodiment of the present disclosure; and

FIG. 20 is an operational flow diagram illustrating one example of a process for forming a semiconductor structure

having devices having freestanding vertical III-V/Ge nanowires on silicon without any buffering according one embodiment of the present disclosure.

DETAILED DESCRIPTION

It is to be understood that the present disclosure will be described in terms of a given illustrative architecture; however, other architectures, structures, substrate materials and process features and steps may be varied within the scope of the present disclosure.

It will also be understood that when an element such as a layer, region or substrate is referred to as being “on” or “over” another element, it can be directly on the other element or intervening elements may also be present. In contrast, when an element is referred to as being “directly on” or “directly over” another element, there are no intervening elements present. It will also be understood that when an element is referred to as being “connected” or “coupled” to another element, it can be directly connected or coupled to the other element or intervening elements may be present. In contrast, when an element is referred to as being “directly connected” or “directly coupled” to another element, there are no intervening elements present.

The present disclosure may include a design for an integrated circuit chip, which may be created in a graphical computer programming language, and stored in a computer storage medium (such as a disk, tape, physical hard drive, or virtual hard drive such as in a storage access network). If the designer does not fabricate chips or the photolithographic masks used to fabricate chips, the designer may transmit the resulting design by physical means (e.g., by providing a copy of the storage medium storing the design) or electronically (e.g., through the Internet) to such entities, directly or indirectly. The stored design is then converted into the appropriate format (e.g., GDSII) for the fabrication of photolithographic masks, which typically include multiple copies of the chip design in question that are to be formed on a wafer. The photolithographic masks are utilized to define areas of the wafer (and/or the layers thereon) to be etched or otherwise processed.

Methods as described herein may be used in the fabrication of integrated circuit chips. The resulting integrated circuit chips can be distributed by the fabricator in raw wafer form (that is, as a single wafer that has multiple unpackaged chips), as a bare die, or in a packaged form. In the latter case the chip is mounted in a single chip package (such as a plastic carrier, with leads that are affixed to a motherboard or other higher level carrier) or in a multichip package (such as a ceramic carrier that has either or both surface interconnections or buried interconnections). In any case the chip is then integrated with other chips, discrete circuit elements, and/or other signal processing devices as part of either (a) an intermediate product, such as a motherboard, or (b) an end product. The end product can be any product that includes integrated circuit chips, ranging from toys and other low-end applications to advanced computer products having a display, a keyboard or other input device, and a central processor.

Reference in the specification to “one embodiment” or “an embodiment” of the present principles, as well as other variations thereof, means that a particular feature, structure, characteristic, and so forth described in connection with the embodiment is included in at least one embodiment of the present principles. Thus, the appearances of the phrase “in one embodiment” or “in an embodiment”, as well any other

variations, appearing in various places throughout the specification are not necessarily all referring to the same embodiment.

Embodiments of the present invention relate generally to field-effect transistors (“FETs”), and more particularly to FETs having a III-V and Ge channel region that is generally vertical with respect to the horizontal plane of the silicon wafer. In the past, vertical FETs were introduced either in a trench or a V-groove to align the channel region of the FET vertically. Therefore, the area of the FET could be reduced because the channel did not use valuable horizontal area leading to a larger die area. However, free-standing III-V and Ge nanostructures on silicon have been difficult to integrate with vertical FETs because of the formation of defects, which act as leakage sources. In addition, III-V epi and Ge epi require different etching chemistries, which makes forming free-standing III-V and Ge nanostructures on a silicon substrate difficult. As will be discussed in greater detail below, embodiments of the present invention overcome this problem by providing position-controlled growth of vertical III-V/Ge nanowires on silicon without any buffering.

Referring now to the drawings in which like numerals represent the same or similar elements, FIG. 1 shows a semiconductor structure **100** at a given point in the fabrication process. For example, FIG. 1 shows a substrate **102** having a plurality well regions **104**, **106** separated by an isolation region **108**. The isolation region **108** defines a plurality of device areas **110**, **112** where one device area **110** is for an n-type device and the other device area **112** is for a p-type device.

In one embodiment, the substrate **102** is a bulk substrate comprising silicon (Si) having a <111> orientation. In other embodiments, the substrate may be a silicon-on-insulator substrate. The well regions **104**, **106** are formed within the substrate **102** using a well implantation process. The well implantation process may include forming a sacrificial oxide layer formed through oxidation to create a screening layer where well implants are to be created. Then, photolithography may be used to selectively define NFET and PFET areas for the wells **104**, **106**, and then implanting ions to form the wells **104**, **106**. A well **104** for an NFET may be formed by implanting p-type species (such as B, BF₂, In, and/or the like), while a well for a PFET is formed by implanting n-type species (such as As, P, Sb, and/or the like). The sacrificial oxide layer may then be removed (e.g., using HF).

FIG. 1 further shows an insulating layer **114** (e.g., SiO₂) is formed and patterned for a subsequent epitaxy process. The insulating layer **114** may be formed by using a deposition process such as atom layer deposition (ALD); chemical vapor deposition (CVD); plasma-enhanced chemical vapor deposition (PECVD); or thermally growing SiO₂ with a process such as rapid thermal anneal (RTA), furnace, or laser anneal on Si substrate. One or more lithography techniques are then performed to pattern the insulation layer **114** where channel structures are to be epitaxially grown. The patterning of the insulation layer **114** forms one or more trenches **116**, **118** in each of the device areas **110**, **112** exposing a top surface of the wells **104**, **106**.

After the insulating layer **114** has been patterned, one or more vertical buffer channel structures **202**, **204** are epitaxially grown at the trenches **116**, **118**. In one embodiment, the buffer structures **202**, **204** comprise gallium arsenide (GaAs) and are grown with an epitaxial process using gas(es), ambient, pressure(s), and temperature(s) with In, Ga, As, SiH₄/H₂, Ge containing precursors. It should be noted that the terms “epitaxially growing”, “epitaxial growth”, “epi-

taxially grown”, and their variants mean the growth of a semiconductor material on a deposition surface of a semiconductor material, in which the semiconductor material being grown has the same crystalline characteristics as the semiconductor material of the deposition surface. In an epitaxial deposition process, the chemical reactants provided by the source gases are controlled and the system parameters are set so that the depositing atoms arrive at the deposition surface of the semiconductor substrate with sufficient energy to move around on the surface and orient themselves to the crystal arrangement of the atoms of the deposition surface. Therefore, an epitaxial semiconductor material has the same crystalline characteristics as the deposition surface on which it is formed. For example, an epitaxial semiconductor material deposited on a {111} crystal surface will take on a {111} orientation. In some embodiments, epitaxial growth and/or deposition processes are selective to forming on semiconductor surface, and do not deposit material on dielectric surfaces, such as silicon dioxide or silicon nitride surfaces.

Examples of various epitaxial growth process apparatus that are suitable for use in one or more embodiments include, e.g., rapid thermal chemical vapor deposition (RTCVD), low-energy plasma deposition (LEPD), ultra-high vacuum chemical vapor deposition (UHVCVD), low pressure chemical vapor deposition (LPCVD), liquid phase epitaxy (LPE), metal organic chemical vapor deposition (MPCVD), atmospheric pressure chemical vapor deposition (APCVD) and molecular beam epitaxy (MBE). A number of different sources can be used for the deposition of the various layers discussed herein. For example, the gas source for the deposition of epitaxial semiconductor material can include a gallium (Ga) and triethylgallium (TEG), AsH₃ gas, trimethylgallium (TMGa) with arsenic (As₄), arsenic sources with a CCl₄ gas source, arsenic (As₂), TdH₄As, etc.

In one embodiment, the buffer structures **202**, **204** are epitaxially grown up from the wells **104**, **106** and extend above a top surface of the insulating layer **114**. The buffer structures **202**, **204** may have a height of 20 nm-200 nm and width of 5 nm-50 nm. However, other dimensions are applicable as well. Once the initial buffer structures **202**, **204** have been formed in each device area **110**, **112** one of the device areas is masked off, as shown in FIG. 3. For example, a material capable of blocking the formation of epitaxy is deposited over the structure **100**. Examples of this material include SiO₂, SiN, OPL (Optical photo layer), etc. The material is patterned through a process involving masking, using industry-standard lithographic techniques, and etching away (e.g., RIE) the unmasked material to form an epi block mask **302** on one side of the structure. In the example shown in FIG. 3, the PFET side **112** comprise the epi block mask **302** while the NFET side **110** remains exposed.

After the epi block mask **302** has been formed, an epitaxial process is performed to form an epitaxial vertical channel layer **304** in contact and surrounding the exposed portions of the unmasked buffer structure(s) **202**. In one embodiment, the epitaxial channel layer **304** contacts the sidewalls and the top surface of the unmasked buffer structure(s) **202**. In the example shown in FIG. 3, the unmasked side of the structure is the NFET side and the epitaxial channel layer **304** may be a III-V material/compound such as indium gallium arsenide (InGaAs). The InGaAs material may have different percentages of In, where InGaAs may be GaAs, In_{0.2}Ga_{0.8}As, In_{0.53}Ga_{0.47}As, In_{0.8}Ga_{0.2}As, InAs, etc. The epitaxial channel layer **304** may have a thickness in the range of 2 nm to 200 nm along the inside GaAs outer line, although other dimensions are applicable as

well. An epitaxial process(es) may be utilized to form/grow the epitaxial channel layer **304** using gas(es), ambient, pressure(s), and temperature(s) with In, Ga, As, SiH₄/H₂, Ge containing precursors.

Once the InGaAs layer **304** has been formed on the NFET buffer structure(s) **202**, the NFET side **112** of the structure **100** is masked with an epi block mask **402**, as shown in FIG. 4. A process similar to that discussed with respect to FIG. 3 may be used to form the epi block mask **402** on the NFET side **110** of the structure while maintain the PFET side **112** exposed. After the NFET epi block mask **402** has been formed, an epitaxial process is performed to form an epitaxial vertical channel layer **404** in contact and surrounding the exposed portions of the unmasked PFET buffer structure(s) **204**. In one embodiment, the epitaxial channel layer **404** contacts the sidewalls and the top surface of the unmasked PFET buffer structure(s) **204**. In the example shown in FIG. 4, the epitaxial channel layer **404** may be Ge and have a thickness in the range of 2 nm-200 nm along the inside GaAs outer line. However, other dimensions are applicable as well. An epitaxial process(es) may be utilized to form/grow the epitaxial channel layer **404** using gas(es), ambient, pressure(s), and temperature(s) with In, Ga, As, SiH₄/H₂, Ge containing precursors. The epitaxial channel layer **404** may be formed/grown using gas(es), ambient, pressure(s), and temperature(s) with Ge containing precursors. CVD techniques may use gas sources such as GeH₄, SiH₄, Si₂H₆, or SiCl₂H₂ for pyrolysis of the precursor gases at elevated temperatures. In at least some embodiments, the vertical channels **304**, **404** have a cylindrical shape and may be referred to as nanowires.

A capping layer **502** is then formed over the structure **100**, as shown in FIG. 5. The capping layer **502** may be formed in contact with a top surface of the insulating layer **114**; sidewalls of the epitaxial channel layers **304**, **404**; and a top surface of the epitaxial channel layers **304**, **404**. The capping layer **502** may comprise, for example, silicon nitride (SiN) and may be formed utilizing one or more processes such as CVD, PECVD, LPCVD, and/or the like. In one embodiment, the capping layer **502** is a non-uniform layer comprising a domed top portion over the epitaxial channel layers **304**, **404** and further comprising angled sidewalls adjacent to the epitaxial channel layers **304**, **404**. An anisotropic etching process, as indicated by the arrows, is then performed to remove the capping layer material from horizontal surfaces, as shown in FIG. 6. This process exposes a top surface of the insulating layer **114** and reduces the amount of capping material above the top surface of the epitaxial channel layers **304**, **404**.

One side of the structure **100** of the structure is then masked off, as shown in FIG. 7. For example, FIG. 7 shows that the NFET area **110** is masked off by forming a masking layer **702** thereon, while the PFET area **112** remains exposed. It should be noted that, in other embodiments, the PFET area **112** may be masked off while the NFET area **110** remains exposed. The masking layer **702** is an epi blocking layer and may comprise SiO₂, SiN, OPL, SiOC(N), etc. The masking layer **702** may be formed similar to the processes discussed above with respect to FIGS. 3 and 4. The insulating layer **114** is then removed from the exposed PFET area **112**. Removal of the insulating layer **114** exposes a bottom surface of the capping layer **502**; a bottom surface of the epitaxial channel layer **404**; and a portion of the sidewalls of the buffer channel layer **204** that were in contact with the insulating layer **114**.

A bottom source/drain layer **704** is then formed using an epitaxy process. Epitaxy of SiGe layers may be formed by

an ultrahigh vacuum chemical vapor deposition system. Silane (SiH₄) may be used as the silicon source. Dilute germane (% GeH₄ in H₂) may be used as a germanium source. % B₂H₂ in H₂ and % PH₃ in H₂ may be used as p-type dopant and n-type dopant. The bottom source/drain layer **704** may either be a source layer or a drain layer. In one embodiment, the bottom source/drain layer **704** formed for the PFET device **112** comprises boron doped germanium (Ge:B). The bottom source/drain layer **706** may contact a top surface of the PFET well **104**; a bottom surface of the epitaxial channel layer **404**; and a portion of the sidewalls of the buffer structure **204** that were in contact with the insulating layer **114**.

A similar process may then be performed for the NFET device **110**, as shown in FIG. **8**. For example, the PFET area **112** is masked off by forming a masking layer **802** thereon, while the NFET area **110** remains exposed. The insulating layer **114** is then removed from the exposed NFET area **110**. An HF based WET or CxF_y, F, CHF_x, SF_x, CF_x based RIE may be used to remove the insulating layer **114**. Removal of the insulating layer **114** exposes a bottom surface of the capping layer **502**; a bottom surface of the epitaxial channel layer **304**; and a portion of the sidewalls of the buffer structure **202** that were in contact with the insulating layer **114**. A bottom source/drain layer **804** is then formed using an epitaxial process similar to the PFET bottom source/drain layer but with parameters, materials, gases, etc. particular to forming the NFET bottom source/drain layer **804**. The bottom source/drain layer **804** may either be a source layer or a drain layer. Epitaxy of SiGe layers may be formed by an ultrahigh vacuum chemical vapor deposition system. Silane (SiH₄) may be used as the silicon source. Dilute germane (% GeH₄ in H₂) may be used as a germanium source. % B₂H₂ in H₂ and % PH₃ in H₂ may be used as p-type dopant and n-type dopant. The bottom source/drain layer **704** may either be a source layer or a drain layer. In one embodiment, the bottom source/drain layer **804** formed for the NFET device **110** comprises silicon doped indium arsenide (InAs:Si). The bottom source/drain layer **804** may contact a top surface of the NFET well **104**; a bottom surface of the epitaxial channel layer **304**; and a portion of the sidewalls of the buffer structure **202** that were in contact with the insulating layer **114**.

A bottom spacer layer **902**, **904** is then formed on the structure **102**, as shown in FIG. **9**. In one embodiment, the bottom spacer **902**, **904** comprises an insulating material (such as silicon oxide, silicon nitride, silicon oxynitride, or a combination of these) and may be formed using any conventional deposition process such as, for example, chemical vapor deposition (CVD) or high density plasma (HDP) CVD, and subsequent etching techniques. The deposited spacer material is then subsequently etched (as indicated by the arrows) to form the final spacer structures. The final spacer structures **902**, **904** respectively contact the top surface of the NFET bottom source/drain **804**; the top surface of the PFET bottom source/drain **704**; a portion of the sidewalls of the NFET and PFET epitaxial channel layers **404**, **304**; and a top surface of the isolation region **108**. In one embodiment, the bottom spacer **902**, **904** is a continuous layer formed over both NFET and PFET devices **110**, **112**.

After the bottom spacer **902**, **904** has been formed, a high-k dielectric layer **1002**, **1004** and metal gate layer **1006**, **1008** is formed on each of the NFET device **110** and PFET device **112**, as shown in FIG. **10**. In one embodiment, the high-k dielectric layer **1002** is formed by blanket depositing a high-k dielectric material deposited over the entire structure **100**, for example by CVD (chemical vapor deposition),

PECVD (plasma enhanced chemical vapor deposition), or ALD (Atomic layer deposition). Excessive high-k gate dielectric material may be removed, for example, by polishing such as chemically mechanical polishing (CMP) and/or etching to form the high-k gate dielectric layers **1002**, **1004**.

The high-k gate material forms the high-k dielectric layer **1002**, **1004** respectively on, in contact with, and conforming to a top surface of the bottom spacer **902**; sidewalls and a top surface of the NFET epitaxial channel structure **404**; and sidewalls and a top surface of the PFET epitaxial channel structure **304**. In one embodiment, the high-k dielectric layer **1002**, **1004** is a continuous layer formed over both is a continuous layer formed over both NFET and PFET devices **110**, **112**. Examples of high-k materials include but are not limited to metal oxides such as hafnium oxide (e.g., HfO₂), hafnium silicon oxide (e.g., HfSiO₄), hafnium silicon oxynitride (Hf_wSi_xO_yN_z), lanthanum oxide (e.g., La₂O₃), lanthanum aluminum oxide (e.g., LaAlO₃), zirconium oxide (e.g., ZrO₂), zirconium silicon oxide (e.g., ZrSiO₄), zirconium silicon oxynitride (Zr_wSi_xO_yN_z), tantalum oxide (e.g., Ta₂O₅), titanium oxide (e.g., TiO₂), barium strontium titanium oxide (e.g., BaTiO₃—SrTiO₃), barium titanium oxide (e.g., BaTiO₃), strontium titanium oxide (e.g., SrTiO₃), yttrium oxide (e.g., Y₂O₃), aluminum oxide (e.g., Al₂O₃), lead scandium tantalum oxide (Pb(Sc_xTa_{1-x})O₃), and lead zinc niobate (e.g., PbZm_{1/3}Nb_{2/3}O₃). The high-k material can further include dopants such as lanthanum and/or aluminum. The stoichiometry of the high-K compounds can vary.

In one embodiment, the metal gate layers **1006**, **1008** are formed by depositing one or more PFET conductive materials over the entire structure **100** and in contact with the high-k dielectric layer **1002**, **1004**. The PFET device **112** is then masked off and one or more NFET conductive materials are deposited over the entire structure **100**. The masking layer is then removed from the PFET device **112**. In other embodiments, the NFET device **110** may be masked off during deposition of the PFET gate layers.

Examples of conductive gate materials include (but are not limited to) polycrystalline or amorphous silicon, germanium, silicon germanium, a metal (e.g., tungsten, titanium, tantalum, ruthenium, zirconium, cobalt, copper, aluminum, lead, platinum, tin, silver, gold), a conducting metallic compound material (e.g., tantalum nitride, titanium nitride, tungsten silicide, tungsten nitride, ruthenium oxide, cobalt silicide, nickel silicide), carbon nanotube, conductive carbon, or any suitable combination of these materials. The conductive gate material may further comprise dopants that are incorporated during or after deposition.

The conductive gate material may comprise multiple layers such as gate work function setting layer (work function metal) and gate conductive layer. The work function metal be deposited employing CVD, sputtering, or plating. The work function metal layers may comprise one or more metals having a function suitable to tune the work function of NFETs or PFETs. In various embodiments, a work function layer may be a conductive nitride, including but not limited to titanium nitride (TiN), titanium aluminum nitride (TiAlN), hafnium nitride (HfN), hafnium silicon nitride (HfSiN), tantalum nitride (Ta₂N), tantalum silicon nitride (TaSiN), tungsten nitride (WN), molybdenum nitride (MoN), niobium nitride (NbN); a conductive carbide, including but not limited to titanium carbide (TiC), titanium aluminum carbide (TiAlC), tantalum carbide (TaC), hafnium carbide (HfC); or combinations thereof. The work function

layer may include multiple layers of work function materials, for example, a work function layer can be a TiN/TiC stack.

FIG. 11 shows that after the metal gates **1006**, **1008** have been formed, an oxide layer **1102** is formed on the entire structure **110** and recessed via, for example, a chemical mechanical polishing (CMP) process. This process polishes the oxide material, metal gates **1006**, **1008**, and dielectric layer **1002**, **1004** below a top surface of the NFET epitaxial channel structure **404** and the PFET epitaxial channel structure **304**. A protective liner **1202**, **1204** such as (but not limited to) silicon nitride is then formed, as shown in FIG. 12. In one embodiment, the protective liner **1202**, **1204** acts as a top spacer layer and contacts a top surface of the oxide layer **1102**; a portion of the sidewalls of the NFET epitaxial channel structure **404**; and a portion of the sidewalls of the PFET epitaxial channel structure **304**. A top surface of the protective liner **1202**, **1204** may be planar with a top surface of the NFET epitaxial channel structure **404**; PFET epitaxial channel structure **304**; and the buffer channel structures **202**, **204**. In one embodiment, the protective liner **1202**, **1204** is a continuous layer formed over both NFET and PFET devices **110**, **112**.

In some embodiments, the buffer structures **202**, **204** may be removed, as shown in FIG. 13. This helps minimize current leakage that may occur with the buffer structures **202**, **204**. The buffer structures **202**, **204** may be removed, for example, by a selective plasma etching technique that removes the buffer structures **202**, **204** selective to the epitaxial channel structures **304**, **404**. In one embodiment, removal of the buffer structures **202**, **204** results in free standing InGaAs and Ge channel structures **304**, **404** on a silicon substrate **102**.

Removal of the buffer structures **202**, **204** also forms trenches **1302**, **1304** exposing inner sidewalls of the NFET epitaxial channel structure **404**; inner sidewalls of the NFET bottom source/drain **804**; inner sidewalls of the PFET epitaxial channel structure **304**; inner sidewalls of the PFET bottom source/drain **704**; and a portion of the top surface of the well areas **104**, **106** of the substrate **102**.

A passivation or capping layer **1402** is then formed on the structure **100**, as shown in FIG. 14. In one embodiment, the capping layer **1402** comprises aluminum oxide (Al_2O_3) and is deposited via ALD. However, other materials/compounds and deposition techniques are applicable as well. For example, the Al_2O_3 may be replaced with or used in combination with HfO_2 , ZrO_2 , SiO_2 , GeO_2 , Si rich GeO_2 , Si/GeO_2 , $\text{SiO}_2/\text{GeO}_2$, Si/SiO_2 , a combination thereof, and/or the like. The capping layer **1402** may contact a top surface of the top spacer **1202**, **1204**; a top surface and inner sidewalls of the NFET epitaxial channel structure **404**; a top surface and inner sidewalls of the PFET epitaxial channel structure **304**; inner sidewalls of the NFET and PFET bottom source drains **804**, **704**; and the exposed top surface of the substrate well areas **104**, **106**. As shown in FIG. 14, the capping layer **1402** may form a "U" shape within the trenches **1302**, **1304**.

FIG. 14 also shows an oxide layer **1404** is formed on the structure **100** via one or more deposition techniques (e.g., SiO_2 by CVD, PECVD, LPPVD following by CMP) after the capping layer **1402** (Al_2O_3 , Si, SiN, GeO_2 , SiO_2 by ALD, CVD, PECVD, PVD) has been formed. The oxide layer **1404** contacts a top surface of the capping layer **1402**, and inner sidewalls and a top surface of the passivation layer **1402** within the trenches **1302**, **1304**. The oxide layer **1404** is then recessed (HF based WET etching, or COR/SiConi based RIE), as shown in FIG. 15. In one embodiment, the

oxide layer **1404** is recessed down below at least the top surface of the top spacer layer **1202**, **1204** using a process such as CMP, a combined gas cluster ion beam (GCIB), and/or the like. This process results in only a portion of the oxide layer **1404** remaining within the trenches **1302**, **1304**. FIG. 15 further shows the capping layer **1402** is removed from the top surface of the top spacer **1202**, **1204**; the surface of the NFET and PFET epitaxial channel structures **404**, **304**; and a portion of the inner sidewalls of the NFET and PFET epitaxial channel structures **404**, **304** within the trenches **1302**, **1304**. In one embodiment, the top surfaces of the capping layer **1402** and oxide layer **1404** remaining in the trenches **1302**, **1304** are co-planar. The capping layer **1402** and oxide layer **1404** provide for better short channel control.

Top source/drains **1602**, **1604** are then formed, as shown in FIG. 16. In one embodiment, each top source/drain **1602**, **1604** extends laterally inward from the portion of the inner sidewalls of its respective NFET and PFET epitaxial channel structure **404**, **304** exposed within the trenches **1302**, **1304**. The source/drains **1602**, **1604** may be formed using a selective epitaxy process. The growth rates may be engineered so that during the epitaxial growth faceted top source/drains **1602**, **1604** are obtained. As shown in FIG. 16, the drains **1602**, **1604** comprise angled sides that angle toward the center of the trenches **1302**, **1304**. The source/drains **1602**, **1604** may comprise in-situ doping (boron, in one embodiment for PFET and phosphorus, in one embodiment, for NFET). In other embodiments, the source/drains **1602**, **1604** may not contain any doping. Doping may be performed using any standard approach such as ion implantation. The source/drain **1602** could be Si doped InAs or similar for an NFET type semiconductor and source/drain **1604** may be P type doped Si, SiGe, or Ge for a PFET type semiconductor.

Silicide regions **1702**, **1704** are then formed on the exposed portions of the top source/drain layers **1602**, **1604**, as shown in FIG. 17. For example, a metal is deposited on top and in contact with the exposed portions of the top source/drain layers **1602**, **1604**. An anneal is then performed to form silicides from the deposited metal and a portion of the top source/drain layers **1602**, **1604**. Unreacted metal is then selectively removed. The metal, in one example, includes cobalt, tungsten, nickel, titanium, platinum, or an alloy or combination thereof. However, other materials are applicable as well. The silicide regions **1702**, **1704** improve source/drain resistance. Additional fabrication processes such as MOL and contact fabrication process may be performed to complete the device.

Referring to FIG. 18, the bottom source/drain layers **704**, **804** discussed above with respect to FIGS. 7 and 8 may be formed using one or more alternative process flows. For example, after the NFET and PFET epitaxial channel structures **404**, **304** are formed sacrificial layers **1802**, **1804** such as silicon nitride layers are formed on sidewalls of the epitaxial channel structures **304**, **404**. The insulating layer **114** is then removed as discussed above and the bottom source/drain layers **704**, **804** are formed. This process also forms faceted epi layers **1806**, **1808** on the top surface of the epitaxial channel structures **304**, **404**. The sacrificial layers **1802**, **1804** are removed and the bottom spacer **902**, **904**; dielectric layer **1002**, **1004**; and metal gates **1006**, **1008**, are then formed as discussed above, as shown in FIG. 19. However, the dielectric layer **1002**, **1004** and metal gates **1006**, **1008** are also formed on the faceted epi layers **1806**, **1808** on the top surface of the epitaxial channel structures **304**, **404**. The oxide layer **1102** is then formed and recessed

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similar to FIG. 11. A polishing/recess process(es) is then performed to remove the faceted epi layers **1802**, **1804** and recess the dielectric and metal gate layers **1002** to **1006** resulting in a structure similar to that shown in FIG. 11. The top spacer layer **120**, **1204** may then be formed as discussed above with respect to FIG. 12.

FIG. 20 is an operational flow diagram illustrating one example of a process for forming a semiconductor structure having devices having freestanding vertical III-V/Ge nanowires on silicon without any buffering according one embodiment of the present disclosure. It should be noted that each of the steps shown in FIG. 20 have been discussed in greater detail above with respect to FIGS. 1 to 19. One or more fin structures, at step **2002**, comprising GaAs are epitaxially grown in contact with a portion of a substrate. A PFET area of the structure, at step **2004**, is masked off and a vertical channel comprising InGaAs is formed in contact with the GaAs fins in the NFET area. The NFET area of the structure, at step **2006**, is masked off and a vertical channel comprising Ge is formed in contact with the GaAs fins in the PFET area.

A capping layer, at step **2008**, is formed in contact with and surrounding the vertical channels. The NFET area, at step **2010** is masked off and a bottom source/drain layer is formed in the PFET area. The PFET area, step **2012** is masked off a bottom source/drain layer is formed in the PFET area. The capping layers, at step **2014**, are removed and a bottom spacer layer is formed in the NFET and PFET areas. NFET and PFET gate structures, at step **2016**, are formed. An oxide layer, at step **2018**, is formed over the structure, wherein the gate structures and oxide layer are subsequently recessed.

A top spacer layer, at step **2020**, is then formed in the NFET and PFET areas. The fin structures in the NFET and PFET areas, at step **2022**, are removed and the resulting trenches are filed with one or more oxide layers. The oxide layers, at step **2024**, are recessed and top source/drain layers are epitaxially grown from the exposed inner sidewalls of the vertical channels in the NFET and PFET areas. Silicide regions, at step **2026**, are then formed in the top source/drain layers. Additional fabrication processes may then be performed to complete the NFET and PFET devices.

Although specific embodiments have been disclosed, those having ordinary skill in the art will understand that changes can be made to the specific embodiments without departing from the spirit and scope of the disclosure. The scope of the disclosure is not to be restricted, therefore, to the specific embodiments, and it is intended that the appended claims cover any and all such applications, modifications, and embodiments within the scope of the present disclosure.

It should be noted that some features of the present disclosure may be used in one embodiment thereof without use of other features of the present disclosure. As such, the foregoing description should be considered as merely illustrative of the principles, teachings, examples, and exemplary embodiments of the present disclosure, and not a limitation thereof.

Also note that these embodiments are only examples of the many advantageous uses of the innovative teachings herein. In general, statements made in the specification of the present application do not necessarily limit any of the various claimed disclosures. Moreover, some statements may apply to some inventive features but not to others.

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What is claimed is:

1. A semiconductor structure comprising at least:
 - a substrate;
 - a first source/drain layer in contact with at least the substrate;
 - a vertical channel comprising one of indium gallium arsenide or germanium in contact with at least the first/source drain layer, wherein the vertical channel is formed above the first source/drain layer and surrounds one or more oxide layers;
 - a gate structure in contact with at least the vertical channel; and
 - a second source/drain layer in contact with at least inner sidewalls of the vertical channel.
2. The semiconductor structure of claim 1, wherein the substrate comprises silicon.
3. The semiconductor structure of claim 1, further comprising:
 - a first spacer layer in contact with at least the first source/drain layer and the vertical channel; and
 - a second spacer layer in contact with the gate structure and the second source/drain layer.
4. The semiconductor structure of claim 3, wherein the gate structure comprises a dielectric layer in contact with the vertical channel, the first spacer layer, and the second spacer layer, and wherein the gate structure further comprises a metal layer in contact with the dielectric layer and the second spacer.
5. The semiconductor structure of claim 1, further comprising:
 - a silicide region in contact with the second source/drain layer.
6. The semiconductor structure of claim 1, wherein the first source/drain layer comprises silicon doped indium arsenide.
7. A semiconductor structure comprising at least:
 - a substrate;
 - a first source/drain layer in contact with at least the substrate;
 - a vertical channel comprising germanium in contact with at least the first source/drain layer, the vertical channel surrounding one or more oxide layers;
 - a gate structure in contact with at least the vertical channel; and
 - a second source/drain layer in contact with at least inner sidewalls of the vertical channel.
8. The semiconductor structure of claim 7, wherein the substrate comprises silicon.
9. The semiconductor structure of claim 7, further comprising:
 - a first spacer layer in contact with at least the first source/drain layer and the vertical channel; and
 - a second spacer layer in contact with the gate structure and the second source/drain layer.
10. The semiconductor structure of claim 9, wherein the gate structure comprises a dielectric layer in contact with the vertical channel, the first spacer layer, and the second spacer layer, and wherein the gate structure further comprises a metal layer in contact with the dielectric layer and the second spacer.
11. The semiconductor structure of claim 7, further comprising:
 - a silicide region in contact with the second source/drain layer.

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12. The semiconductor structure of claim 7, wherein the one or more oxide layers comprise at least one of:

- Al₂O₃;
- HfO₂;
- ZrO₂;
- SiO₂;
- GeO₂;
- Si rich GeO₂;
- Si/GeO₂;
- SiO₂/GeO₂; and
- Si/SiO₂.

13. The semiconductor structure of claim 7, wherein the first source/drain layer comprises boron doped germanium.

14. A method for forming a semiconductor structure, the method comprising:

- forming, for one or more fin structures each comprising gallium arsenide, a channel layer comprising indium gallium arsenide or germanium in contact with the fin structure and an insulating layer;
- forming, for the one or more fin structures, a sacrificial layer in contact with sidewalls of the channel layer and the insulating layer;
- removing, for each of the one or more fin structures, at least a portion of the insulating layer; and
- forming, for each of the one or more fin structures, a bottom source/drain layer in place of the insulating layer.

15. The method of claim 14, wherein forming the bottom source/drain layer further forms a faceted epitaxial layer in contact with a top surface of the channel layer.

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16. The method of claim 15, further comprising: removing, for each of the one or more fin structures, the sacrificial layer; and

forming, for each of the one or more fin structures, a spacer layer in contact with the bottom source/drain layer and the channel layer.

17. The method of claim 16, further comprising: forming, for each of the one or more fin structures, a gate dielectric layer in contact with the faceted epitaxial layer, the channel layer, and the spacer layer; and forming, for each of the one or more fin structures, a gate metal layer in contact with the gate dielectric layer.

18. The method of claim 17, further comprising: depositing an oxide layer; and recessing the oxide layer below a top surface of the one or more fin structures.

19. The method of claim 18, further comprising: etching, for each of the one or more fin structures, the gate dielectric layer and the gate metal layer down below the top surface of the fin structure; removing, for each of the one or more fin structures, the faceted epitaxial layer; and forming an additional spacer in contact with at least a top surface of the oxide layer, a top surface of the gate dielectric layer, and a top surface of the gate metal layer.

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